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A novel method for device-related electroencephalography artifact suppression to explore cochlear implant-related cortical changes in single-sided deafness

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HIGHLIGHTS

- Cortical activity localization in CI users via qEEG is confounded by device artifacts.
- We observed significant characteristic peaks in frequency domain from CI users' EEG.
- CI artifacts in EEG data could be effectively removed with band-limited ICA.
- By applying band-limited ICA, CI users' cortical activity can be evaluated effectively.

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ABSTRACT

Background: Quantitative electroencephalography (qEEG) is effective when used to analyze ongoing cortical oscillations in cochlear implant (CI) users. However, localization of cortical activity in such users via qEEG is confounded by the presence of artifacts produced by the device itself. Typically, independent component analysis (ICA) is used to remove CI artifacts in auditory evoked EEG signals collected upon brief stimulation and it is effective for auditory evoked potentials (AEPs). However, AEPs do not reflect the daily environments of patients, and thus, continuous EEG data that are closer to such environments are desirable. In this case, device-related artifacts in EEG data are difficult to remove selectively via ICA due to over-completion of EEG data removal in the absence of preprocessing.
New methods: EEGs were recorded for a long time under conditions of continuous auditory stimulation. To obviate the over-completion problem, we limited the frequency of CI artifacts to a significant characteristic peak and apply ICA artifact removal.
Results: Topographic brain mapping results analyzed via band-limited (BL)-ICA exhibited a better energy distribution, matched to the CI location, than data obtained using conventional ICA. Also, source localization data verified that BL-ICA effectively removed CI artifacts.
Comparison with existing method: The proposed method selectively removes CI artifacts from continuous EEG recordings, while ICA removal method shows residual peak and removes important brain activity signals.
Conclusion: CI artifacts in EEG data obtained during continuous passive listening can be effectively removed with the aid of BL-ICA, opening up new EEG research possibilities in subjects with CIs.

1. Introduction

More than 200,000 patients with profound hearing loss have been rehabilitated using cochlear implants (CIs) (Kral and O'Donoghue, 2010), devices that bypass a nonfunctional inner ear and directly stimulate the auditory nerve. Also, cochlear implantation has recently emerged as a possible surgical treatment option

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for rehabilitation in subjects having single-sided deafness (SSD) with tinnitus (Arndt et al., 2011; Song et al., 2013b; Vermeire and Van de Heyning, 2009). From a neuroscientific viewpoint, cochlear implantation affords a unique opportunity to study cortical plastic changes associated with unilateral or bilateral profound hearing loss and auditory sensory restoration (Lee et al., 2007; Song et al., 2015a; Song et al., 2014b; Song et al., 2015c; Song et al., 2015d). To explore such plastic changes related to cochlear implantation, neuroimaging modalities such as positron emission tomography (PET), functional magnetic resonance imaging (fMRI), magnetoencephalography (MEG), and quantitative electroencephalography (qEEG) have been employed.

Of these various methods, fMRI or MEG cannot be easily performed on subjects with metal implants, and repetitive PET examinations should be minimized to avoid overexposure to radiation, whereas qEEG can be performed repeatedly, without any associated hazard following cochlear implantation. In this regard, qEEG is the most effective method used to analyze ongoing cortical oscillations in CI users. However, localization of the cortical resting state or auditory evoked potentials (AEPs) in CI users via qEEG is confounded by the presence of a stimulus artifact produced by the device per se. Hence, development of a reliable method of suppression of device-associated artifacts from the EEG stream is a prerequisite if qEEG is to be employed as a neuroimaging tool in subjects with CIs.

To suppress CI-induced noise, the use of AEP-based EEG measurements of very short duration, triggered by extremely brief sound stimuli, has been suggested (Viola et al., 2012). An AEP-based EEG measurement method typically evaluates repeat signals triggered by identical stimulations and averages the data to reduce noise. Such preprocessing, or averaging of repeat signals, affords an appropriate environment for artifact removal. CI-related artifact signaling is correlated with the AEP because such signaling is in fact the source of the AEP per se. Hence, the pattern of CI artifacts can be observed and separated from the AEPs and background brain activities via independent component analysis (ICA) (Gilley et al., 2006; Viola et al., 2012). This approach, however, does not reflect the daily environments of patients; the AEP-based approach uses a very short, particular sound, such as a click.

In this context, EEG measurements taken during passive listening to a continuous sound stimulus (such as music) over several minutes may afford more natural brain activation upon sound stimulation than the AEP approach. However, removing CI-related artifacts from EEG data obtained during continuous passive listening is difficult, unlike the case with AEP data, because preprocessing the signals is not possible as no repeat signals exist to be averaged. Therefore, the data are very noisy and may contain numerous signals from many brain activities not associated with auditory stimuli. As ICA thus cannot be used to separate independent sources, thereby identifying artifactual signals, the artifact-independent source is admixed with other brain activities. Unfortunately, the auditory brainstem response (ABR) is one signal admixed with the CI artifact. Therefore, rejection of CI artifact-independent sources via ICA may remove important brain information as well as the CI artifact.

The main objective of the present study was to develop a novel method of suppressing EEG stream energy from a CI. To selectively control only the artifactual signal, we applied an ICA artifact removal method described in previous studies. As applying ICA artifact removal methods to continuous EEG data obtained while passively listening to continuous auditory stimuli is difficult, we tested modified ICA methods including sub-band decomposition ICA (SD-ICA) (Tanaka and Cichocki, 2004) and band-selective ICA (BS-ICA) (Zhang and Chan, 2006) in an attempt to solve the problem of ICA failure. As spectral analysis includes examining the characteristics of the CI artifact spectrum, limitation of the frequency band to focus on CI artifact characteristics in the frequency domain may effectively discard many irrelevant sources and facilitate ICA-mediated artifact removal. In the current study, we describe CI artifact removal from specific bands in the EEG streams of four patients with CIs using band-limited (BL)-ICA. Source localization and comparison of spectra are performed to confirm suppression of CI artifacts with preservation of brain activities associated with cortical auditory evoked responses.

2. Materials and methods

2.1. Subjects and EEG recordings

Four patients with unilateral acquired SSD and ipsilateral tinnitus underwent cochlear implantation using Med-EL devices (see Table 1 for further information). The duration of deafness ranged from 9 months to 10 years (median, 4.5 years), and all patients had left SSD (Table 1).

EEGs were recorded under two conditions: condition 1, CI switch-on with a continuous music stimulus at most comfortable loudness (MCL) level of each patient monaurally to the implant using a cable; condition 2, CI switch-off with no auditory stimulus. Under both conditions, EEGs were recorded for 5 min using WinEEG software version 2.84.44 (Mitsar, St. Petersburg, Russia; http://www.mitsar-medical.com) in a fully lit room shielded against sound and stray electric fields, with the eyes closed and all patients sitting upright. The EEG streams were sampled using 19 electrodes of the standard 10–20 International placement, referenced to linked ears. The impedances of all electrodes were maintained below 5 kΩ throughout the EEG recordings. Data were recorded at a sampling rate of 1024 Hz using a 0.15-Hz high-pass filter and a 200-Hz low-pass filter. After recording, all data were processed off-line by resampling to 128 Hz and band-pass filtering (employing a fast Fourier transform filter with application of a Hanning window) at 2–44 Hz and next imported into Eureka! software (Sherlin and Congedo, 2005). Antwerp University Hospital Ethics Committee reviewed and approved the study and all applicable documents prior to study initiation. All patients signed an approved informed consent in order to be enrolled into the study.

All participants abstained from alcohol for 24 h prior to EEG recording and from caffeinated beverages on the day of the recording to avoid alcohol- or caffeine-induced changes in EEG power (Logan et al., 2002; Siepmann and Kirch, 2002; Volkow et al., 2000). The vigilance of all participants was checked by monitoring of EEG streams to prevent drowsiness-induced changes such as slowing of the alpha rhythm or the appearance of spindles (Moazami-Goudarzi et al., 2010); no participant exhibited any drowsiness-related EEG change.

Table 1
Demographic characteristics of the included subjects.

Subject number	Duration of deafness	Psychoacoustic characteristics of tinnitus	Name of the implanted device (in detail, please)	Side of the cochlear implant
1	4 years	Pure tone	MED-EL Sonata ti 100 FLEX Soft electrode	Left
2	5 years	Pure tone	MEDEL Sonata ti 100 FLEX Soft electrode	Left
3	9 months	Pure tone	MED-EL Sonata ti 100 FLEX 24 electrode	Left
4	10 years	Narrow band noise	MED-EL Pulsar ci 100 Standard electrode	Left