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Research paper

Electrically evoked compound action potential artifact rejection by independent component analysis: Technique validation☆

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ABSTRACT

The electrically-evoked compound action potential (ECAP) is the synchronous whole auditory nerve activity in response to an electrical stimulus, and can be recorded in situ on cochlear implant (CI) electrodes. A novel procedure (ECAP-ICA) to isolate the ECAP from the stimulation artifact, based on independent component analysis (ICA), is described here. ECAPs with artifact (raw-ECAPs) were sequentially recorded for the same stimulus on 9 different intracochlear recording electrodes. The raw-ECAPs were fed to ICA, which separated them into independent sources. Restricting the ICA projection to 4 independent components did not induce under-fitting and was found to explain most of the raw-data variance. The sources were identified and only the source corresponding to the neural response was retained for artifact-free ECAP reconstruction. The validity of the ECAP-ICA procedure was supported as follows: N_1 and P_1 peaks occurred at usual latencies; and ECAP-ICA and artifact amplitude-growth functions (AGFs) had different slopes. Concatenation of raw-ECAPs from multiple stimulus currents, including some below the ECAP-ICA threshold, improved the source separation process. The main advantage of ECAP-ICA is that use of maskers or alternating polarity stimulation are not needed.
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1. Introduction

This paper presents a novel artifact rejection procedure for electrically-evoked compound action potentials (ECAPs) based on Independent Component Analysis (ICA). This new method, denoted ECAP-ICA, avoids the use of masker pulses or alternating polarity stimulus pulses.

1.1. Artifact rejection in ECAP measurements

ECAPs reflect the synchronous whole auditory nerve (AN) response to electrical stimulation. ECAPs are routinely used in clinics to objectively measure the functionality of auditory nerve activation. A stimulation artifact results from a voltage decay following the biphasic current pulse. The artifact waveform is usually several orders of magnitude larger than the ECAP and is a decaying exponential with a time constant of several hundreds of microseconds, which is sufficiently long to overlap with the neural response. Two main artifact cancellation methods are available in clinical software: the use of alternating stimulus polarity, or forward-masking (ECAP-FM).

As shown schematically in Fig. 1, four buffers are recorded in the forward masking method. On buffer C, a preceding masker-pulse is used to set the auditory nerve in a refractory state and therefore only the probe artifact is recorded, along with any remaining masker artifact and response. The artifact is obtained by subtracting the effects of the masker alone (buffer D) from buffer C. ECAP is finally obtained by subtracting the artifact (buffers C-D) from buffer A (ECAP and artifact) from which the effect of amplifier-switch-on (buffer B) has been subtracted. Hence, the subtraction (A)-(C-D)-(B) results in ECAP-FM.

The alternating polarity method requires two buffers to be recorded and summed together: one resulting from a cathodic-first

List of abbreviations: AN, auditory nerve; CI, cochlear implant; CI24RE, Cochlear® Nucleus Freedom™ cochlear implant – 22 active electrodes and 2 ground electrodes; ECAP, electrically-evoked compound action potential; ECAP-FM, ECAP obtained with the forward-masking technique; ECAP-ICA, ECAP obtained with the ICA artifact rejection technique; ICA, independent component analysis; IC, independent component (or source); JADE-R, joint approximate diagonalisation of the cross-cumulants eigenmatrices (computational implementation of ICA); MP1, extracochlear ground electrode; MP2, ground electrode placed on the case of the cochlear implant; N1P1, peak-to-peak voltage difference measurement of ECAP amplitude; RMS, root mean square; SNR, signal to noise ratio

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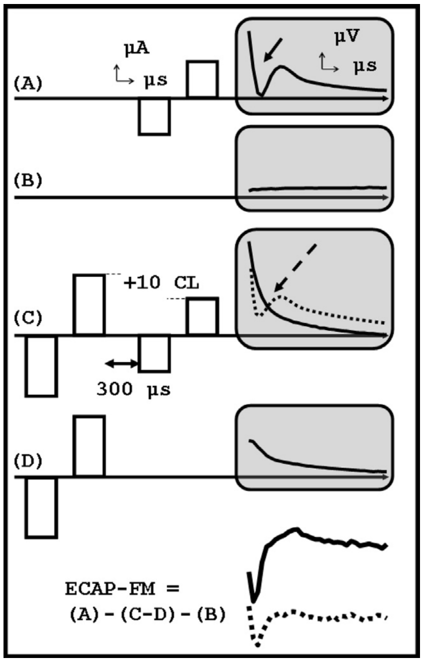

Fig. 1. Forward-masking ECAP artifact subtraction paradigm (ECAP-FM). Each buffer (grey windows) is an average of fifty consecutive recordings. Buffer A (referred to as raw-ECAP) is the superposition of ECAP elicited by the probe biphasic electrical pulse, indicated by an arrow, and the probe stimulation artifact. Buffer C records the probe artifact and no probe ECAP, along with the remaining masker artifact and masker ECAP. If the masker fails to render the auditory nerve completely refractory, a residual probe response remains (dashed line). Buffer D records the influence of the masker alone, and buffer B records the amplifier switch-on effect. The ECAP-FM revealed by subtraction is plotted in the bottom: if incomplete masking occurs in buffer C, the ECAP-FM is distorted and underestimated due to subtraction of the residual ECAP response.

biphasic pulse and the other resulting from an anodic-first biphasic pulse. It is assumed that the artifacts in the two cases are exactly equal amplitude but opposite polarity and hence cancel each other, and that the neural responses to both polarity pulses are identical, making their sum equal to the ECAP with double the amplitude.

Both of these methods rely upon physiological assumptions that are known to be only approximately true. In the case of forward masking, all of the auditory nerve fibers may not be in a refractory state when the probe stimulus follows the masker, leading to a partial probe ECAP that is subsequently subtracted from the probe ECAP in buffer A (Brown et al., 1990 -see also dashed waveform on buffer C in Fig. 1). In the alternating polarity method, anodic-first and cathodic-first biphasic stimulus pulses do not generate the same auditory nerve activity: the ECAPs have different latencies and amplitudes, resulting in distorted ECAPs after addition (Miller et al., 2000). Moreover, our own measurements in saline suggested that stimulation artifacts are not exactly equal and opposite for the two polarities, leading to a substantial residual artifact in the final ECAP. Two recent signal processing studies have been conducted to enhance traditional alternating polarity and forward-masking techniques (Alvarez et al., 2007, 2008). For both alternating polarity and forward-masking, the recorded buffers were weighted before subtraction in order to result in ECAP waveforms as close as possible to the description of a good ECAP waveform (as defined by clinical visual observation). In these studies, a very large ECAP database was used, in which each ECAP waveform was rated by expert audiologists. However, it is unclear how to relate these weighting coefficients to physiological or physical phenomenon.

A third artifact rejection technique called ‘precision-triphasic pulse artifact rejection technique’ (Bahmer et al., 2010), uses a triphasic pulse with a small portion of the charge of the first phase (around 10%) allocated to a third phase. This method, like ECAP-ICA, avoids the use of masker pulses or alternating polarity. However, triphasic pulses induce a different excitation pattern than clinically-used biphasic pulses. A fourth technique was introduced by Klop et al. (2004) who used an electrical amplifier with a compensation circuit at the input to reduce the residual stimulation artifact by electrical subtraction, and found they could reduce the time course of the artifact from around 200 μs to less than 30 μs. This technique has not yet been implemented in clinical cochlear implant (CI) settings.

1.2. Independent component analysis: a denoising technique for ECAP artifact cancellation

ICA is a blind-source-separation technique based on higher-order statistics that aims to separate independent sources from linear mixtures recorded on different sensors (for computational details see e.g. Comon, 1994; Bell and Sejnowski, 1995; Cardoso, 1999; Hyvarinen and Oja, 2000). It should be noted that no *a priori* knowledge is required about the sources. ICA decomposes the recordings into sources that are maximally statistically independent. The ICA rationale applies the central limit theorem that stipulates that the more independent the sources in a mixture, the more Gaussian the mixture’s probability density function: the less Gaussian a variable’s distribution is, the more independent it is assumed. Gaussianity is measured by kurtosis: zero kurtosis implies a Gaussian distribution. After ICA, it is then up to the experimenter to interpret these sources as relevant physical phenomenon. Finally, the position and number of sensors available are important parameters for ICA success: ICA demands at least the same number of sensors as the expected sources (Hyvarinen et al., 2001). More sensors than sources may help ICA to determine the independent relationship between the sources; however additional sensors may be redundant.

ICA has been used to separate artifact in cochlear implant cortical recordings (Gilley et al., 2006; Castaneda-Villa and James, 2011; Viola et al., 2011). In these studies, ICA was applied to multi-channel recordings of cortical potentials from scalp electrodes. The CI stimulation induces a large artifact described as an artifact pedestal followed by an overshoot period that can overlap with the target cortical response. The ICA approach requires simultaneous recording of artifact + cortical response mixtures at different locations on the scalp. However, current ECAP recording technology allows recordings to be made on only one intracochlear electrode at a time. Thus, in the ECAP-ICA method described here, ICA was applied to multiple intracochlear telemetry recordings of the ECAP + artifact + noise mixture (raw-ECAPs) obtained sequentially on different recording electrodes. It was assumed that the physical phenomena generating the electrical stimulation artifact and the ECAP would be exactly the same for each sequential recording, as they would be in simultaneous recordings. Artifact, ECAP, and noise separation is theoretically possible provided that those signals behave independently from each other. To verify that ECAP-ICA was a genuine physiological auditory nerve response and was successfully separated from the artifact, the following criteria were applied:

1. ECAP-ICA waveforms should have the typical N1-P1 pattern, with peak latencies in the range of those obtained by other methods such as ECAP-FM. The ECAP-ICA amplitudes should be broadly consistent with the range of ECAP amplitudes reported in the literature.
2. ECAP amplitude should increase with stimulus level at a different rate to the artifact amplitude. If sufficiently low stimulus levels are used, ECAP amplitude should reach zero

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