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Application of triphasic pulses with adjustable phase amplitude ratio (PAR) for cochlear ECAP recording: I. Amplitude growth functions

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ABSTRACT

This study describes the use of triphasic electrical stimulation pulses with an adjustable phase amplitude ratio (PAR) for the reduction of electrical stimulus artifacts. It is hypothesized that the setting of a certain PAR can facilitate a nearly artifact-free recording of electrically evoked compound action potentials (ECAP) in the cochlea. Artifact reduction with triphasic pulses using single epochs is expected to prevent latency or polarity effects, which are seen in standard forward masking or alternating polarity strategies.

Although the application of a third phase is already implemented in implants manufactured by MED-EL (Zierhofer, 2003) and Cochlear (Sydney, Nucleus 5 System; van Dijk et al. (2007)) for the reduction of stimulation artifacts generated with these stimulators in ECAP measurements, an elaborate systematic evaluation of PAR for artifact reduction has not yet been conducted (compare evaluation for one subject Schoesser et al. (2001)). In the present paper, the effect of PAR variation on human ECAP recording and the feasibility of amplitude growth function recording with triphasic pulses and an optimized PAR are evaluated. Measurements were accomplished in five subjects, whereby more detailed test series were carried out in one subject. All subjects were implanted with devices from the company MED-EL, Innsbruck. A comparison of PAR optimized triphasic pulses was carried out against two other measurement techniques (biphasic alternating polarity stimulation and biphasic stimulation according to Miller) for apical, middle, and basal electrodes. ECAP thresholds were estimated by means of amplitude growth functions. However, recording of ECAP with triphasic pulses showed drawbacks: additional artifacts depending on stimulation and/or recording parameters are introduced, the ratio between the additional artifact and improved detectability of neural responses is dependent on PAR, and response thresholds obtained with triphasic pulses – although similar in shape – are in most cases substantially higher compared to thresholds measured with the Miller method. Higher thresholds most probably occur because the triphasic pulse patterns seem to less effectively stimulate neural structures compared to biphasic pulses since measured response thresholds are higher. For certain electrode groups threshold profiles obtained with triphasic pulses were found to be similar compared to stimulation with biphasic pulses.

1. Introduction

Current cochlear implant systems allow the recording of electrically evoked compound action potentials (ECAPs). ECAPs are small voltages generated by the auditory nerve in response to electrical stimulation. The latency of the ECAP is 0.2–0.4 ms after stimulus onset and consists of two phases differing in polarity, namely the N (negative) and P (positive) peaks. The recording of ECAPs is a method to investigate spiral ganglion integrity and the survival of nerve fibers. Correlations have been found between ECAP's and hearing thresholds as well as between the ECAP recovery function and speech performance. However, these results are not consistent in the literature (Miller et al., 2008; Lai and Dillier, 2007; Battmer et al., 2005; Turner et al., 2002; Kiefer et al., 2001; Abbas and Brown, 1991).

The recording of ECAPs is difficult as there is a large electrical stimulation artifact. Several stimulation paradigms have been developed to reduce this artifact. One of these paradigms suggests that alternating pulses with sequentially changing phase patterns can cancel out artifacts by using opposing polarities (alternating polarity, Brown and Abbas (1990)). Forward masking paradigms (de Sauvage et al., 1983; Brown et al., 1990) or improved forward masking paradigms (Miller et al., 2000) use the refractoriness of the auditory nerve to separate artifacts from neural responses. Scaled template paradigms involve the recording of sub-threshold

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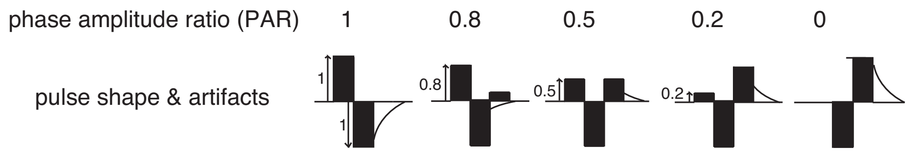

Fig. 1. Pulse shapes of precision triphasic pulses and induced artifacts (curved line at each right pulse edge) with different phase amplitude ratios (PAR).

measurements containing the stimulus artifact, which are scaled to and then subtracted from supra-threshold measurements (see Miller et al., 1998). These paradigms have the disadvantage of a possible non-linear tissue charge behavior, polarity and latency effects, and/or lack of knowledge about the limits of absolute refractory period (Morsnowski et al., 2006). Triphasic pulses have been proposed as stimuli for ECAP recordings in order to circumvent these drawbacks because for ECAP recording only a single measurement cycle is required (no application of polarity alternation or scaled templates) and are therefore employed in certain cochlear implant stimulators (see e.g. Zierhofer, 2003; van Dijk et al., 2007). The employed stimulation with triphasic pulses for artifact reduction in theses stimulators are applied in a different manner than described in the present manuscript.

Generally, current cochlear implant devices apply biphasic current pulses that consist of two opposing polarities. Both polarities can depolarize auditory nerve fibers and generate action potentials (Wieringen et al., 2008). The charge-balanced triphasic pulse pattern consists of three consecutive phases alternating in polarity. Applied in ECAP measurements, triphasic pulses may minimize artifacts (e.g. from transition electrode/electrolyte) by restoring the neural membrane to its resting potential faster than biphasic pulses do (Eddington et al., 2004). A potential application of this stimulus is to compensate for the interaction between pulses subsequently applied at different electrode locations; and to reduce the artifacts induced by electrical stimulation in ECAPs and brainstem responses recordings (Bahmer et al., 2010a). In the latter case, large artifacts can hamper the recordings (e.g. van den Honert and Stypulkowski, 1986).

Until now, the application of triphasic pulses in ECAP recordings has not been investigated elaborately and systematically (compare Schoesser et al. (2001)). The configuration of triphasic pulses with three adjustable phase amplitudes can be described by their phase amplitude ratio (PAR, see Fig. 1). It is unclear how the phase amplitude ratio (PAR) of triphasic pulses can be optimized in human subjects in order to reduce the stimulation artifact. This may be dependent on electrode location and patient specific conditions. Even the total amplitude of the triphasic pulse may have an influence on the optimal PAR. Therefore, in this study we carried out ECAP recordings with triphasic pulses in different configurations in order to optimize the PAR. In addition, neural thresholds and corresponding electrode profiles obtained by analysis of amplitude growth functions were compared with thresholds from standard stimulation and recording techniques. Measurements were accomplished in six subjects at three different electrode locations; one subject (S1) underwent more detailed measurements with recordings collected at 11 electrode contacts. In the present study, we investigated the following:

- ECAP recordings with triphasic pulse stimulation.
- Residual artifact depending on phase amplitude ratio.
- Application of triphasic pulses for recording amplitude growth functions.
- Comparison of neural thresholds from standard recording techniques (two pulse subtraction, alternating polarity) with triphasic stimulation.

In the companion paper the application of triphasic pulses for recording recovery functions and ECAP response strengths for various pulse shapes/polarity was evaluated.

2. Methods

2.1. Characterization of precision triphasic pulses

The generation of biphasic, triphasic, and precision triphasic pulse patterns is implemented in current PULSARci100 and SONATAti100 stimulators (MED-EL, Innsbruck, Austria). Although triphasic pulse stimuli are not available for speech strategies, they provide an alternative to standard biphasic stimulation in the detectability of neural responses elicited by electrical stimulation. A triphasic pulse pattern consists of two phases with equal polarity and one phase with an opposite polarity (+/−/+or −/+/−). Triphasic pulses with equal phase duration and an adjustable relation of first and third phase amplitudes have been termed "precision triphasic pulses" in the context of MED-EL implants. To balance total charge, the sum of the amplitudes of the two pulse phases with the same polarity equals the amplitude of the pulse phase with opposing polarity. For the precision triphasic pulses, the ratio between the two pulse phases with equal polarity can be set. For instance, if the first phase is set to 80% of the maximum amplitude, the third pulse phase (same polarity) is 20% of the maximum amplitude as shown in Fig. 1. The amplitude of the third phase is calculated and automatically set by the stimulator. Precision triphasic pulses allow pulse amplitude adjustments in order to minimize residual artifacts (Eddington et al., 2004; Schoesser et al., 2001). Standard biphasic pulse stimulation generates residual resting artifacts (Fig. 1). In theory, if the amplitude of the third phase of the precision triphasic pulse is correctly adjusted, the residual artifact should be completely canceled. However, we experienced residual artifacts since the setting of the amplitude ratio between first and last phase for the most effective artifact reduction depends on individual measurement conditions. Therefore, the setting may differ among subjects and electrodes and deserves special attention.

2.2. Subjects S1–S5

Recordings were assessed in five subjects (S1–S5; age 46–76 years) at one basal, middle, and apical electrode contact. Demographic data and stimulation parameter is given in Table 1. Most comfortable level (MCL) values were determined with measurement stimulation patterns and the evoked potential research system EAPRS (details in the following section). Additional recordings on all available electrode contacts (electrode contact 2 excluded due to irregular responses) were performed in subject S1. Impedances (in kΩ) for each electrode contact were 1: 7.58, 3: 6.05, 4: 5.63, 5: 4.51, 6: 4.16, 7: 3.75, 8: 4.44, 9: 5.00, 10: 4.37, 11: 4.23, 12: 5.35. The MCL determined with a research interface system (RIB2 system, details in the following section) for electrode contacts 1–5 was 1039, 6–7: 1134, 8: 1039, 9: 945, 10–11: 1039, 12: 945 current units (CU, 1 CU equals 1 μA with a linear scaling). MCL was determined with triphasic pulse stimuli equal to the ECAP recording stimulation (50 repetitions, pulse phase duration 30 μs, temporal gap between each phase (interphase gap) 2.1 μs).