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Research paper

Interaural stimulation timing in single sided deaf cochlear implant users

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ABSTRACT

The interaural time difference (ITD) is an important cue for the localization of sounds. ITD changes as little as 10 μs can be detected by the human auditory system. By provision of one ear with a cochlear implant (CI) ITD are altered due to the partial replacement of the peripheral auditory system. A hearing aid (HA), in contrast, does not replace but adds a processing delay component to the peripheral auditory system extending ITD. The aim of the present study was to quantify interaural stimulation timing between these different modalities to estimate the need for central auditory temporal compensation in single sided deaf CI users or bimodal CI/HA users. For this purpose, wave V latencies of auditory brainstem responses evoked either acoustically (ABR) or electrically via the CI (EABR) have been measured. The sum of delays consisting of CI signal processing measured in the MED-EL OPUS2 audio processor and EABR wave V latencies evoked on different intracochlear sites allowed an estimation of the entire CI channel-specific delay for MED-EL MAESTRO CI systems. We compared these values with ABR wave V latencies measured in the contralateral normal hearing or HA provided ear in different frequency bands. The results showed that EABR wave V latencies were consistently shorter than those evoked acoustically in the unaided normal hearing ear. Thus, artificial delays within the audio processor can be implemented to adjust interaural stimulation timing. The currently implemented group delays in the MED-EL CI system turned out to be reasonably similar to those of the unaided ear. For adjustment of CI and contralateral HA, in contrast, an adjustable additional across-frequency delay in the range of 1–11 ms implemented in the CI would be required. Especially for bimodal CI/HA users the adjustment of interaural stimulation timing may induce improved binaural hearing, reduced need for central auditory temporal compensation and increased acceptance of the CI/HA provision.

1. Introduction

The interaural time difference (ITD) is the difference in arrival time of a sound between the two ears. ITDs are determined by the head size and range from 0 μs (for sounds straight ahead) to about 700 μs (for sounds directly to one side of the listener). With Equation (1), ITD can be calculated by using the approximation that the head is a hard sphere with two point receivers (ears) (Moore, 2012).

$$ITD = 30\frac{\mu s}{cm}*r*(\theta + \sin(\theta)); \text{ with r : head radius in cm; } \theta \text{ : angle to sound source} \quad (1)$$

Equation (1) can be applied when the sound source is located in the horizontal plane. For an extended view on ITD calculations see Xie (2013).

The human auditory system is very sensitive to changes in ITD. The just noticeable difference of ITD was 10 μs in low-frequency sinusoids (Yost, 1974). As the head size is subject to a growth process ITDs vary during lifetime. Typically the head circumference is about 40 cm for 3-month-old boys (WorldHealthOrganization,

Abbrevations: ITD, Interaural time differences; CI, Cochlear implant; HA, Hearing aid; SSD, Single sided deaf; ABR, Acoustically evoked auditory brainstem response; EABR, Electrically evoked auditory brainstem response; RF, Radio frequency

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2014) and about 58 cm for adults (Bushby et al., 1992). Thus ITD changes due to the growth process are typically in the range of approx. 200 µs. The central auditory system seems to deal with this variation successfully. Hence, ITD perception is adaptive to some extent.

Therapy of hearing loss with hearing aids (HA) and cochlear implants (CI) alters and/or extends ITDs in the order of several milliseconds, more than an order of magnitude greater than the physiologic ITD variation related to head growth. The aim of this work was to compare interaural stimulation timing in listeners provided with a MED-EL MAESTRO CI system and a contralateral ear with normal hearing also referred to as single sided deaf (SSD) CI users or patients provided with a CI and a HA contralaterally (bimodal CI users). The comparison was based on recordings of auditory evoked potentials (auditory brainstem responses –ABR) and on measurements of group delays in a common type of CI system (MED-EL MAESTRO) and in various HA. A measure of the temporal compensatory performance that is requested from the central auditory system in such patients may help to understand their issues in binaural summation and squelch effect (Arndt et al., 2011; Vermeire and Van de Heyning, 2009).

1.1. Nonlinear frequency mapping in the peripheral hearing organ

Auditory sensations in the unaided ear start with a sound wave entering the outer ear canal. After passing through, the sound wave stimulates the tympanic membrane to vibrate. For passing through the ear canal, a sound wave needs 74 µs assumed an ear canal length of 2.5 cm. The mechanical vibration of the tympanic membrane is then transferred by the ossicular chain to the oval window, a membrane between middle and inner ear. Phase diagrams of middle-ear transfer functions offer small phase differences that increase non-linearly with frequency. Thus, group delays of the middle ear are not constant, but small (max. 250 µs for 1–3 kHz, see Gan et al. (2004)). Subsequently, the transduction of mechanical vibration into nerve action potentials is mediated by the basilar-membrane within the inner ear exhibiting delays that increase non-linearly with distance from the cochlear base (i.e. traveling-wave delay). The phase response of the inner-ear transfer function shows relatively large phase differences that increase with distance from the cochlear base. Cochlear group delays vary from approx. 1 ms for high frequency sounds to more than 8 ms for low frequency sounds (Ruggero and Temchin, 2007). Added together these delays are named τ_{Ear} in Fig. 1. By vibrations of the basiliar membrane respective sensory receptor cells are stimulated and release neurotransmitter into the synaptic cleft, the adequate stimulus to excite auditory nerve fibers. This mechano-electrical transduction process is nearly frequency-independent and takes about 1 ms (Temchin et al., 2005) and is marked by $\tau_{Synaptic}$ in Fig. 1.

1.2. Delays in the hearing aid induced hearing process

Current digital HA pick up sound signals in front of the ear canal or above the pinna and filter, compress and amplify them. Ensuing, the processed sound signals are directed into the outer ear canal. Afterwards, the physiologic hearing process starts. HA processing extends the acoustic pathway compared to a non-aided ear by τ_{HA} (see Fig. 1). Dillon et al. (2003) investigated τ_{HA} in five digital HA and found more or less frequency-independent values between 3 and 11 ms. The signal processing components that mainly determine τ_{HA} are the analog-to-digital and digital-to-analog converters and spectral analysis using typically block-based algorithms such as the fast Fourier transform (Kates, 2005; Stone and Moore, 1999).

1.3. Delays in the CI-induced hearing process

A cochlear implant (CI) bypasses the peripheral auditory system and stimulates the auditory nerve using biphasic current pulses applied by intracochlear electrodes. CI signal processing mimics auditory signal processing of the normal hearing ear in some aspects. The broadband input signal is transduced from an acoustic wave to a voltage signal by a microphone. After high-pass filtering (pre-emphasis), analog-digital converting and automatic gain controlling, an array of bandpass filters is used to split up the broadband input into different frequency bands mimicking the filter properties of the basilar membrane. Band-specific envelopes are then detected and used to modulate the amplitude of trains of biphasic current pulses that are applied to intracochlear electrodes and stimulate auditory nerve fibers. The time delay between microphone and electrode introduced by the CI system is named τ_{CI} (see Fig. 1). τ_{CI} is determined by mainly three components in the MED-EL OPUS2 audio processor, namely the across-frequency delay inserted by the analog-to-digital converter and the frequency-specific group delay of the CI bandpass filter bank depending on the type of filter. In the OPUS2 a bank of finite impulse response (FIR) filters with linear phase and therefore constant group delay within (but not across) filtersis implemented.

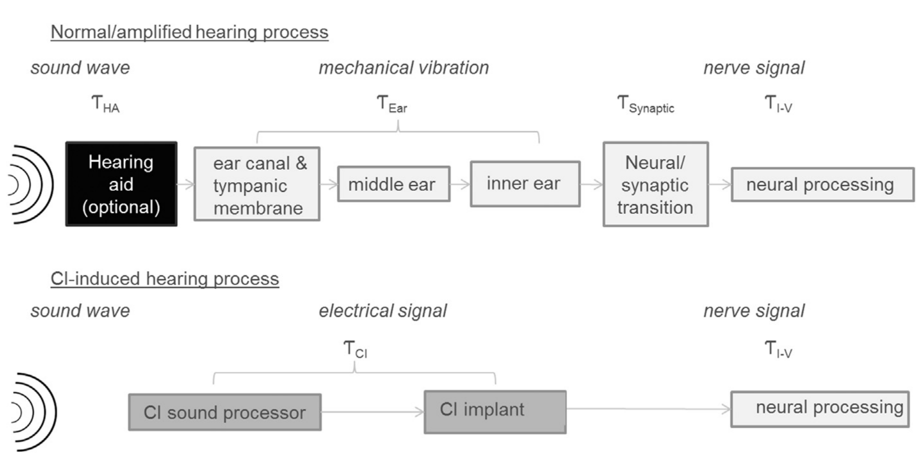

Fig. 1. Signal transmission in the two peripheral auditory pathways of SSD CI or bimodal CI/HA users. The delay components are marked with τ. Every component contributes to (E) ABR wave V latency (compare Equation (3)).