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Hearing Research 218 (2006) 64–71

Hearing Research

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Research paper

# The effect of center frequency and bandwidth on the auditory evoked magnetic field

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Received 15 October 2005; received in revised form 14 April 2006; accepted 27 April 2006
Available online 23 June 2006

**Abstract**

Auditory evoked magnetic fields in relation to the center frequency of sound with a certain bandwidth were examined by magnetoencephalography (MEG). Octave band, 1/3 octave band, and 130 Hz bandwidth noises were used as the sound stimuli. All signals were presented at 60 dB SPL. The stimulus duration was 500 ms, with rise and fall ramps of 10 ms. Ten normal-hearing subjects took part in the study. Auditory evoked fields were recorded using a 122 channel whole-head magnetometer in a magnetically shielded room. The latencies, source strengths and coordinates of the N1m wave, which was found above the left and right temporal lobes around 100 ms after the stimulus onset, were analyzed. The results demonstrated that the middle frequency range had shorter N1m latencies and larger N1m amplitudes, and that the lower and higher frequency stimuli had relatively delayed N1m latencies and decreased N1m amplitudes. The N1m amplitudes correlated well to the loudness values in the frequency ranges between 250 and 2000 Hz. The source locations of N1m did not reveal any systematic changes related to the center frequency and bandwidth.

*Keywords:* Magnetoencephalography; Auditory evoked response; N1m; Loudness; Center frequency; Bandwidth

## 1. Introduction

The effect of sound intensity in the auditory cortex has been previously investigated by magnetoencephalography (MEG), and auditory evoked magnetic field (AEF) in response to stimulus intensity has been examined (Reite et al., 1982; Bak et al., 1985; Pantev et al., 1989a; Vasama et al., 1995). These results indicate that the N1m amplitude of the AEFs increases up to a stimulus intensity of 50–60 dB SPL, but then remains more or less constant or even decreases for higher intensities. The intensity dependence of the equivalent current dipole (ECD) location in space has also been examined. Pantev et al. (1989a) examined the influence of stimulus intensity on the depth of the ECD of wave N1m. They reported that the higher the stimulus intensity is, the more superficial is the locus of cortical excitation. Vasama et al. (1995), however, failed to find any systematic variation of the N1m source locations as a function of intensity.

The subjective aspect of sound intensity is loudness. Loudness is the attribute of auditory sensation in terms of which sounds may be ordered on a scale extending from quiet to loud. Loudness is what we experience in daily life. Someone can speak loudly or softly and the volume of an audio device can be turned up or down. The mechanisms underlying the perception of loudness are not fully understood. The idea that loudness is simply proportional to the total number of action potentials fired by all auditory nerve neurons (the spike count hypothesis) have been investigated in animal studies. The spike count hypothesis was tested and justified that the rate-of-growth of both loudness and the auditory nerve spike count agreed over a wide

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*Abbreviations:* ANOVA, analysis of variance; AEF, auditory evoked field; ECD, equivalent current dipole; MEG, magnetoencephalography; fMRI, functional magnetic resonance imaging

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doi:10.1016/j.heares.2006.04.002

range of tone intensity (Zwislocki, 1965; Goldstein, 1974; Lachs et al., 1984). However, disagreement also exists (Pickles, 1983; Relkin and Doucet, 1997).

In previous studies on MEG response as a function of frequency, the ECD locations, that is, tonotopic organization, have been studied in considerable detail. Relatively little research has been conducted on amplitude response as a function of frequency. The N1m response amplitude as a function of frequency has been examined using pure tones, and the results showed that the N1m amplitude peaks at 1000 Hz (Pantev et al., 1995). However, other researches have indicated that the N1m amplitude remains fairly constant, independent of test frequency (Pantev et al., 1988; Lütkenhöner et al., 2003). Regarding the representation of noise in auditory cortex, auditory single-unit responses in the superior temporal gyrus of monkeys have been examined (Rauschecker et al., 1995; Rauschecker and Tian, 2000; Lakatos et al., 2005). Responses of lateral neurons to bandpass noise are stronger than responses to pure tones. Functional magnetic resonance imaging (fMRI) has showed that pure tones activate primarily the core, whereas bandpass noises activate preferably the belt areas in human auditory cortex (Wessinger et al., 2001). Relatively little is known about the response amplitude in human auditory cortex as a function of frequency and bandwidth. The present study aimed to evaluate the magnetic activity of the auditory cortex elicited by sounds as a function of frequency and bandwidth.

## 2. Materials and methods

Ten normal-hearing subjects (22–35 years old; all right-handed) took part in the MEG experiment. Eight normal-hearing subjects (22–35 years old; all right-handed) took part in loudness experiment. They all had normal audiological status and no history of neurological diseases. Informed consent was obtained from each subject after the nature of the study was explained. The study has been approved by the ethics committee of the National Institute of Advanced Industrial Science and Technology (AIST).

Octave band, 1/3 octave band, and 130 Hz bandwidth noises with center frequencies of 250, 500, 1000, 2000, 4000 and 8000 Hz were used as stimuli. The octave band noises have fixed bandwidth in a logarithmic frequency scale. The 130 Hz bandwidth noises have fixed bandwidth irrespective of center frequency, like pure tone. The white noises were filtered using fourth-order Butterworth filters. Center frequencies of the noise bands are given as the geometric means of low- and high-frequency cutoffs. The stimulus duration was 500 ms, including rise and fall ramps of 10 ms. Stimuli were presented monaurally to the right ear through plastic tubes and earpieces inserted into the ear canals. To check the frequency characteristics of the stimuli, signals were measured with an ear simulator that included a microphone, a preamplifier, and an adaptor connected to the earpiece. The power spectra of some of the stimuli measured with the ear simulator are presented in Fig. 1. All signals were presented at 60 dB SPL.

The AEFs were recorded using a 122-channel whole-head DC superconducting quantum interference device (DC-SQUID) magnetometer (Neuromag-122™; Neuromag Ltd., Helsinki, Finland) in a magnetically shielded room (Hämäläinen et al., 1993). Three experimental sessions, each with a different bandwidth, were carried out. In each session, stimuli were presented in randomized order with a constant interstimulus interval of 1.5 s. To maintain a constant vigilance level, the subjects were instructed to concentrate on a self-selected silent movie that was being projected on a screen in front of them and to ignore the stimuli. The magnetic data were sampled at 400 Hz after being bandpass filtered between 0.03 and 100 Hz, and then averaged approximately 50 times. Responses were rejected if the magnetic field exceeded 3000 fT/cm in any channel. The averaged responses were digitally filtered between 1.0 and 30.0 Hz. The analysis time was 0.7 s from 0.2 s prior to the stimulus onset. The average of the 0.2 s prestimulus period served as the baseline. The Neuromag-122™ has two pick-up coils in each position that measure two tangential derivatives, $\partial B_z/\partial x$ and $\partial B_z/\partial y$, of the field component $B_z$. To evaluate the latency of the N1m peak, the root-mean-squares of $\partial B_z/\partial x$ and $\partial B_z/\partial y$ were determined as the amplitude of the responses at each recording position. The peak latency having the maximum value of the root-mean-square in the latency range from 70 to 130 ms over each left and right hemisphere was defined as the N1m latency in each subject.

To estimate the location of the underlying neural activity of the N1m wave, a single moving ECD was assumed as the source of the magnetic field of the N1m wave in a head-based coordinate system. The ECDs that best described the measured magnetic field at the N1m peak latencies were found by least-squares fitting in a spherical head model. A one-dipole model was used separately for the left and right hemispheres, with a subset of 18–28 channels over each hemisphere as shown in Fig. 2. The origin of this coordinate system was set at the midpoint of the medio-lateral axis ($y$-axis) which joined the center points of the entrance to the acoustic meatuses of the left and right ears. The posterior-anterior axis ($x$-axis) was oriented from the origin to the nasion, while the inferior-superior axis ($z$-axis) was perpendicular to the $x-y$ plane. Only ECDs explaining >80% of the recorded magnetic field were accepted for further analyses. Stimulus type had no significant effect on the dipole location, as will be shown in Section 3. Thus, for the estimation of the dipole waveforms, the dipole location was assumed to be the same for all stimuli. The dipole location based on the averaged responses to all six stimuli of a session was first calculated separately for the left- and right-hemisphere data by least-squares fitting in a spherical head model. After that, the dipole waveforms for all stimuli were calculated using the fixed-dipole approach in each hemisphere. The maximum peak dipole waveform in the latency range from 70 to 130 ms over each left and right hemisphere was defined as the N1m ECD moment in each subject.