Noninvasive Direct Stimulation of the Cochlear Nerve for Functional MR Imaging of the Auditory Cortex

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Summary: We herein present our preliminary experience with functional MR imaging of the direct electrical stimulation of the cochlear nerve using an MR imaging-compatible electrode placed in the external auditory meatus of five patients with binaural sensorineural hearing loss. The stimulator was placed outside the imager’s bore and introduced a different approach by placing the stimulator de-
tifacts caused by the nerve stimulator (2). We took results are severely degraded by susceptibility ar-
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promontory test has been encouraging, al-
vasive and objective method is
Therefore desirable. A noninvasive objective meth-
method was developed using an auditory canal electrode (1). Previous experience with functional MR imaging as an objective tool with which to evaluate the promontory test has been encouraging, although the method is still slightly invasive and the results are severely degraded by susceptibility artifacts caused by the nerve stimulator (2). We took a different approach by placing the stimulator device outside the imager’s bore and introduced a stimulating ball electrode in the external auditory meatus.

Technique

We used a modified MED-EL Electro Audiometer (MED-EL Corporation, Innsbruck, Austria) for electrical stimulation during MR imaging. This device is commonly used for the preoperative testing of cochlear implant candidates. It consists of a control and display box (transmitter) and a two-channel receiver-stimulator (left and right ear) to generate the stimulation current. The stimulation electrode (silver ball) is placed in the external auditory meatus near the eardrum, and the reference electrode can be placed either on the skin of the forehead or on the skin of the patient’s neck. The control box permitted the selection of all stimulation parameters (63 Hz–2 kHz, 1.6–1613 μA) and triggered the stimulation (single 500-millisecond or continuous 5-Hz stimulation bursts, see Fig 1B-C). Data were transferred between the control box and the receiver-stimulator by infrared transmission.

This Electro Audiometer was tested for MR compatibility at 1.5 T (Magnetom VISION, Siemens Medical Systems, Erlangen, Germany) by performing a performance test, an evaluation of artifacts, an in vitro and in vivo evaluation of temperature increase, and an evaluation of stimulation signal changes. Temperature was measured using a calibrated fluo-
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tion. The remaining time for safe imaging is 0.35 seconds for current bursts used for electrical stimulation and image acquisition.

**Fig 1.** Experimental setup and the different stimulation schemes used for the electrical stimulation of the auditory nerve during functional MR imaging. Stim. Sig., stimulation signal (stimulation information is transmitted from the control box of the Electro Audiometer, and the signal is generated in the receiver-stimulator); Rph, photo resistor impedance; Rdr, dark resistance of photo resistor; Pat. Sig., stimulation signal transmitted to patient; MR-Trig., MR-trigger signal; Im. Ac., image acquisition.

A. The entire stimulation setup is located within the shielded room. The electrode leads are disconnected by means of two photo resistors. The light for switching the photo resistors is transmitted via two optical fibers. The Electro Audiometer synchronizes the stimulator-receiver (receiver 2) and light source (receiver 1) by infrared transmission. Furthermore, the light source synchronizes the MR imager with the stimulation setup by applying an MR trigger signal to the imager after the photo resistors have disconnected the electrodes. State A (no stimulation) and state B (stimulation) are realized by a “beam shutter.”

B, Schematic diagram depicts synchronization between the current bursts used for electrical stimulation and image acquisition. The remaining time for safe imaging is 0.35 seconds for mode 1.

C, Schematic diagram depicts synchronization between the current bursts used for electrical stimulation and image acquisition. The remaining time for safe imaging is 0.7 seconds for mode 2.

imager, two photo resistors were used to disconnect the electrodes. The light for switching the photo resistors is transmitted via two optical fibers. The Electro Audiometer synchronizes the stimulator-receiver and light source by infrared transmission. Furthermore, the light source synchronizes the MR imager with the stimulation setup by sending a trigger signal to the MR imager after the photo resistors have disconnected the electrodes. State A (no stimulation) and state B (stimulation) can be realized by a beam shutter (eg, hand), connecting or disconnecting infrared transmission and therefore triggering or stopping the stimulation process. The entire stimulation setup is located within the shielded room, which is important to avoid RF-induced artifacts (Fig 1).

After flushing the external auditory meatus of the patient with physiologic saline, the stimulating electrode was placed in the external auditory meatus and fixed with earplugs. The reference electrode was placed on the forehead by using MR imaging-compatible carbon ECG electrodes. The individual stimulation thresholds were ascertained before moving the patient into the imager. All patients experienced severe binaural sensorineural hearing loss and were cochlear implant candidates. During stimulation, they reported a hearing sensation of intermediate loudness, with the stimulus well below electrical discomfort. Stimulation consisted of 125 to 1000 Hz sine tone bursts at a pulse rate of 1 Hz (stimulation mode 1) or 5 Hz (stimulation mode 2), respectively. The stimulating current ranged from 150 to 650 μA.

We used a multi-section gradient-echo echo-planar imaging sequence (9600/46 [TR/TE]; flip angle, α = 90°; number of sections, four; section thickness, 5 mm; intersection gap, 2.5 mm; field of view, 250 mm; matrix, 64 × 64; number of acquisitions, 1; phase encoding, left-right). The whole sequence was repeated every 3 seconds, according to the stimulation protocol. One hundred twenty measurements were recorded with the resting and stimulating condition alternating after 10 measurements. The sections were oriented in the transverse plane, with the most cranial section at the level of the superior temporal gyrus. Image analysis was performed using the AFNI software package (R. Cox, Medical Center of Wisconsin) using a modified smoothed boxcar reference function for cross-correlation analysis and a threshold of .22 < r < 0.36 corresponding to a P value of <0.05. A cluster size of 500 to 600 μL (5 voxels) seemed sufficient to differentiate activation from scattered background noise. Measurements one through three of every time series were discarded to account for nonequilibrium effects. We used section-by-section motion correction. This correction was performed within AFNI with in-plane translation and rotation (three-parameter rigid body transformation). The results of the functional studies were superimposed onto anatomic gradient-echo images. In three of five patients, we observed an activation of the superior temporal gyrus, which was unilateral in two patients (contralateral to stimulation) and bilateral in one (predominantly contralateral to stimulation) (Fig 2). In two patients, no activation could be visualized because...
of severe motion artifacts in one case and problems with positioning of the stimulating electrode in the other. The clinical histories of these two patients were not different from those of patients in whom functional MR imaging was successful. A repeated examination was not performed. Available data being very preliminary, we did not observe any tonotopic organization nor was there any visible or measurable effect of stimulus presentation rate or intensity on activation.

**Discussion**

Acoustic stimulation of the primary auditory cortex and the associated areas has been reported in the functional MR imaging literature (6). Functional MR imaging used to study the auditory cortex is hampered by the loud noise inherent in echo-planar imaging sequences, which is superimposed onto the acoustic stimuli. This problem, however, does not apply to patients with severe sensorineural hearing loss. Previous functional MR imaging studies of deaf patients have shown the feasibility of functional MR imaging to study the direct electrical stimulation of the cochlear nerve with subsequent activation of the auditory cortex (2, 7). The techniques presented, however, were slightly invasive in that they required the insertion of the stimulation electrode either close to the round window membrane or at the cochlear promontory, in both cases necessitating the perforation of the tympanic membrane and the use of local anesthesia. Apart from being noninvasive, the novel method presented in this article is not limited by susceptibility artifacts. The potential clinical applications include the presurgical diagnostic workup of cochlear implant candidates (especially after prelinguistic auditory deprivation) in whom the functionality of the auditory pathways can be documented in an objective way. In addition to this, differentiation of central from peripheral and organic from functional hearing loss could be of clinical use.

**References**