Hearing loss from the acoustic artifact of the coil used in extracranial magnetic stimulation

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Article abstract—The stimulating coil used in extracranial magnetic field stimulation (EMFS) emits a high intensity impulse sound artifact that causes permanent threshold shifts in the unprotected ears of experimental animals. At magnetic stimulation levels of 50 to 100%, the magnetic coil acoustic artifact (MCAA) ranged from 145 to 157 dB peak sound pressure level at the eardrum. The magnetic field alone did not appear to cause hearing impairment since no threshold shifts were observed in ears that were plugged with ear protectors during exposure to the MCAA. These findings suggest that the acoustic artifact produced by EMFS in the clinic may pose some risk for hearing loss in patients and clinicians when held in close proximity to the unprotected ear. We recommend the use of ear protectors for the patient and clinician during EMFS as a precautionary measure to prevent hearing loss.

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Magnetic field stimulation of neural tissue is a recently developed technique adapted clinically for stimulating the peripheral and central nervous systems.[1,2] Investigators have used extracranial magnetic field stimulation (EMFS) of the human motor cortex to evoke muscle action potentials and motor responses.[2,3] In contrast to conventional electrical transcranial stimulation, magnetic stimulation offers the advantage of being noninvasive and painless, and causes no serious discomfort to the patient. However, it is not known whether high levels of or repeated exposures to magnetic stimulation will adversely affect sensory-neural tissues and physiologic processes over time. Also, during EMFS stimulation, the stimulating coil emits a high-intensity acoustic impulse artifact. High-intensity impulse sounds in close proximity to the ear may induce sensorineural hearing impairment.[4] In facial nerve stimulation, for example, the coil is generally positioned in the temporal or parieto-occipital region of the cranium, a few centimeters from the ear.[5,6] From this position, the high-intensity magnetic coil acoustic artifact (MCAA) is transmitted to the unprotected middle and inner ears with little attenuation.

We investigated the effects of the MCAA associated with EMFS on auditory sensitivity in rabbits using auditory evoked brainstem responses (ABR).[7] We measured permanent threshold shifts (PTS) 3 or more weeks after exposing the animals to varying levels of the MCAA.

Methods. *Animals.* Fifteen albino and chinchilla rabbits were used in this study, and 18 ears were unilaterally exposed to EMFS levels ranging from 50 to 100%.

Magnetic stimulation. A Cadwell Model MES 10 with the standard, small magnetic coil was used for stimulation. This instrument, with the 5-cm diameter, 1.5-cm thick coil, has an effective magnetic field radius of about 4.5 cm. The plastic-covered coil was positioned at approximately 1 to 2 cm from the inner pinna with the apex of the coil directed at the external auditory meatus. Fifty single-current pulses were presented at approximately 4-second intervals at EMFS levels 50%, 60%, 70%, 80%, 90%, and 100% of the maximum output (peak magnetic induction = approximately 2.2 tesla at 100% charging of the capacitor).

Sound pressure measurements. The sound pressure levels (SPLs) of the acoustic artifact were measured on a Bruel and Kjaer (B & K) Model 2636 amplifier (linear mode/peak hold) and a B & K 4170 probe assembly with a 4134 ½-inch microphone placed at 1 to 2 cm from the entrance to the pinna for measurements of the MCAA at the outer ear, and at the position of the rabbit tympanic membrane (in the head of a nonliving preparation). The diaphragm of the recording microphone was beyond the effective radius of (and unaffected by) the magnetic field during the SPL measurements. The microphone signal was fed to a B & K 2636 amplifier (bandwidth, 22.4 Hz to 200 kHz). All SPL readings were maximum peak values with a rise time of 5 dB/μsec. The waveform and spectrum of the acoustic artifact were analyzed with a Model 3561A Hewlett Packard Analyser and viewed on a Nicolet 2290-III oscilloscope. All measurements were made in a sound-isolated room.

ABR recordings. For ABR measures, the animals were anesthetized with pentobarbital (30 mg/kg body weight) and

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placed in a sound-attenuated chamber. ABR recordings were made from the scalp using stainless steel electrodes.[7] The active electrodes were placed subcutaneously on the vertex (positive) and in the retro-auricular area of the ear under test. The ground electrode was placed in the lower back. The electrical potentials were amplified (10K) and filtered (50 to 4,700 Hz with an 18-dB per octave rolloff), and fed directly to a Data Lab 4000 signal averager. Signals exceeding ±1 V after amplification are automatically rejected. Sweeps of 512 were sampled at intervals of 20 µsec. An average of 2,064 epochs were monitored on the display screen and reproduced in hard copy. ABR waveforms were examined in dB steps from suprathreshold to threshold levels, with at least 2 trial sequences being repeated near threshold to confirm the reliability and validity of responses. PTS were measured by ABR at 1, 2, 4, 6, 8, 12, and 16 kHz 3 or more weeks after the magnetic stimulation session. The stimulus consisted of bandpass-filtered single sine waves presented at a rate of 20 per second. Each sine wave was set at the center frequency of a 1/1 or 1/3 octave bandpass filter (B & K 1617) with about 48 dB per octave and maximum attenuation of about 75 dB, further attenuated by a Hewlett Packard 350D and a Fonema attenuator. The stimuli were transduced by a TDH 39 earphone that was attached to a funnel and a 1-dm long rubber tube, tightly sealed deep in the ear canal.

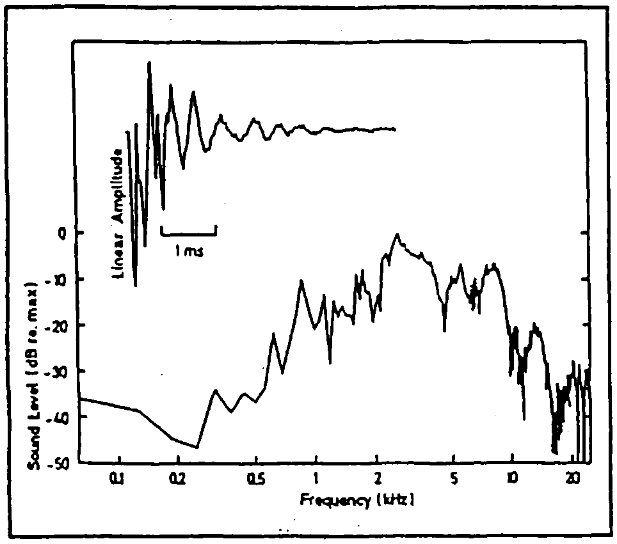

Figure 1. The spectrum and time-course (inset) of the acoustic artifact generated by the magnetic coil used in EMFS.

Results. *Acoustic analysis of the magnetic coil acoustic artifact.* Figure 1 illustrates the spectrum and time course (inset) of the MCAA generated by the rapidly expanding coil during stimulation. This figure shows that the acoustic artifact is an impulse signal that is essentially a broad band click with peak acoustic energy between 2 and 5 kHz. The predominant acoustic energy of click is concentrated in the 1st 200 µsec. The acoustic spectrum showed little variation for magnetic stimulus levels from 50% to 100%. The impulse sounds generated by the coil were 149 dB peak SPL at an EMFS level (percentage reading of EMFS on the Cadwell MES 10) of 60%, 153 dB at 70%, and 154 dB maximum peak SPL at the 80% stimulus level (measured at the position of the eardrum). International standards for damage risk criteria indicate that sounds with peak pressure levels of

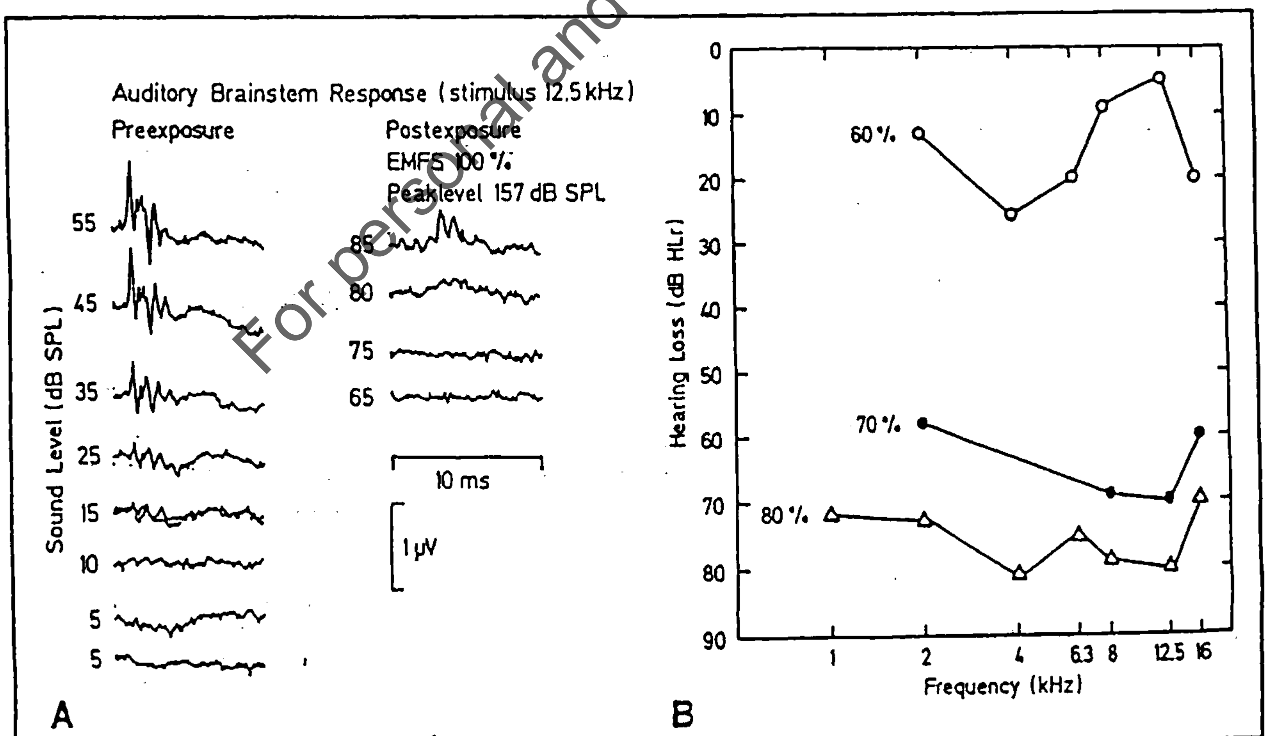

Figure 2. (A) Sample ABR recordings in a rabbit from suprathreshold to threshold level at 12.5 kHz before and after exposure to 50 EMFS pulses at 100% of maximum output. (B) Audiograms illustrating the permanent threshold shifts measured in 3 different rabbits after exposure to magnetic coil acoustic artifact levels of 149, 153, and 154 dB, respectively, corresponding to EMFS levels of 60, 70, and 80%.

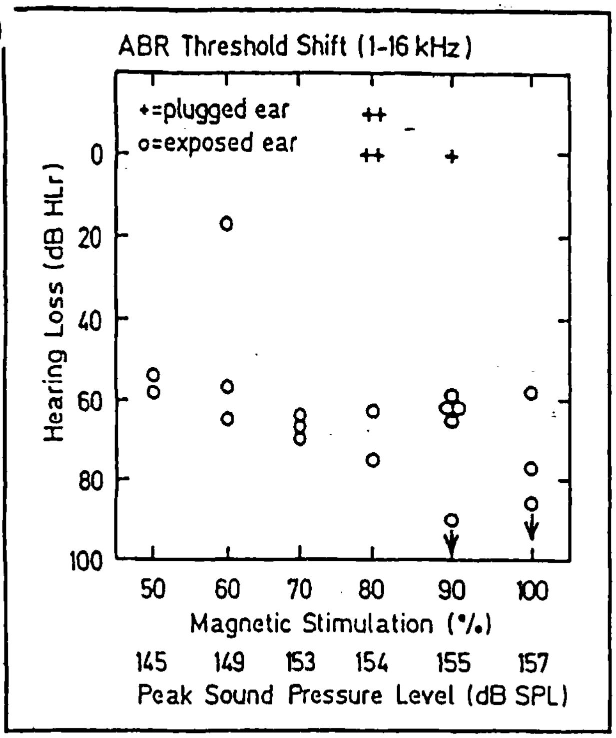

Figure 3. Permanent threshold shifts (PTS) for individual animals exposed to EMFS levels of 50 to 100% and corresponding MCAA levels of 145 to 157 dB, presented as the average of thresholds at octaves from 1 to 16 kHz.

110 to 140 dB may be unsafe.[8]

Auditory brainstem response thresholds. A permanent increase in auditory threshold represents damage to the stereocilia of cochlear hair cells and associated sensorineural structures and processes. Animals tested for PTS 3 to 4 weeks after exposure to MCAA levels of 50% to 100% were found to have a considerable shift (increase) in auditory thresholds in the low, mid, and high frequency ranges. Figure 2A illustrates sample ABR responses from threshold to suprathreshold levels at 12.5 kHz in 1 animal before and after exposure to 50 EMFS pulses at 100%. This figure shows that the ABR measured within hours after exposure to the MCAA of 157 dB is shifted by 70 dB. Figure 2B shows the gradation in permanent hearing loss observed in 3 ears after exposure to MCAA SPLs of 149 dB (60% EMFS), 153 dB (70% EMFS), and 154 dB (80% EMFS) measured at the eardrum. This figure shows that exposures to the MCAA associated with increased magnetic stimulation may result in mild to moderate to severe hearing loss. The threshold shifts observed in the low frequency range at 2 kHz and at 12 and 16 kHz indicate MCAA-induced damage in a wide area of the cochlea.

A summary of the PTS found in 18 ears following exposure to EMFS levels of 50 to 100% (corresponding to MCAA levels of 145 to 157 dB, measured at the eardrum) as determined by ABR is presented in figure 3. In this figure, the PTS values are presented as the average of thresholds at octaves from 1 through 16 kHz for each ear tested. These findings indicate increasing hearing loss as a function of increased steps in the EMFS and associated MCAA levels.

To determine whether the threshold shifts were due to the MCAA exclusively, 5 ears were plugged with standard energy-absorbent earplugs, sealed with a removable silicone base impression material, and exposed to 50 stimuli at EMFS levels of 80 and 90 (corresponding to MCAA peak SPL values of 154 and 155 dB measured at the eardrum). Auditory thresholds measured immediately after MCAA exposure indicated no hearing loss beyond the normal variability of the test procedure in the protected (plugged) ears.

Discussion. Several recent studies have investigated the potentially harmful effects of EMFS in humans. However, these studies focused on the effects of EMFS on neural structures[9] and on cognitive and other cerebral functions.[10] The potential risk of exposure to the acoustic artifact associated with EMFS has been given little or no attention in studies of magnetic stimulation.

Exposure to high-intensity impulse noise will result in hearing impairment in human ears.[11] However, the damaging effects of brief impulse noises are often underestimated by the observer since the brief sounds do not appear loud due to the relatively long time constant of human auditory perception.[12]

Another magnetic device used in magnetic resonance imaging is also known to produce an intense acoustic artifact that has been reported[13] to be a potential cause of hearing loss in patients with unprotected ears.

The absence of a hearing loss in plugged ears suggests that the MCAA, rather than the magnetic field, is responsible for the observed hearing loss.

The PTS observed in the experimental animals of this study suggest that the MCAA is a potential hazard to human ears that are frequently or repeatedly exposed to EMFS levels of 50% to 100%. We recommended as a prudent course the use of earplug inserts or earmuffs for the patient and clinician during EMFS testing at percentage levels of 50% and above.

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