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PNS Limits for Human Head-Size MPI Systems: Preliminary Results

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Abstract

Magnetic Particle Imaging (MPI) utilizes kHz-range sinusoidal drive fields to excite magnetic nanoparticles. These time-varying magnetic fields induce electric fields within the human body, which in turn can induce peripheral nerve stimulation (PNS), also known as magnetostimulation. In this work, we report the preliminary results of human subject experiments for human head-size MPI systems. These experiments were performed on a solenoidal head coil that achieved an order of magnitude reduction in the voltages needed to generate the targeted magnetic fields.

I. Introduction

In magnetic particle imaging (MPI), time-varying magnetic fields are utilized to perform imaging via scanning the field free point (FFP) over a field-of-view (FOV). Previous studies have shown that peripheral nerve stimulation (PNS), also known as magnetostimulation, is the main safety constraint for the drive field in MPI [1–3]. According to these studies, PNS limits decrease with frequency [1], and depend on the direction of the applied field [2–4], as well as its duration and duty cycle [5, 6]. In addition, the thresholds also correlate with the anatomical measures of the body part that is exposed to the field [1, 7].

Recently, there has been a growing interest in human head-size MPI systems for applications such as functional imaging and stroke imaging [8, 9]. To investigate the PNS limits in the head, we have previously presented the design of a magnetostimulation head coil that achieves an order of magnitude reduction in the voltages needed to generate the required magnetic fields [10]. In this work, we present the preliminary results of human-subject magnetostimulation experiments in the head for the drive field in MPI.

II. Methods and Materials

II.I. Magnetostimulation Head Coil

The design constraints of the magnetostimulation coil were determined based on the following model [1]:

$$\Delta B_{min} = \frac{\lambda_{fit}}{r_{eff}} \tag{1}$$

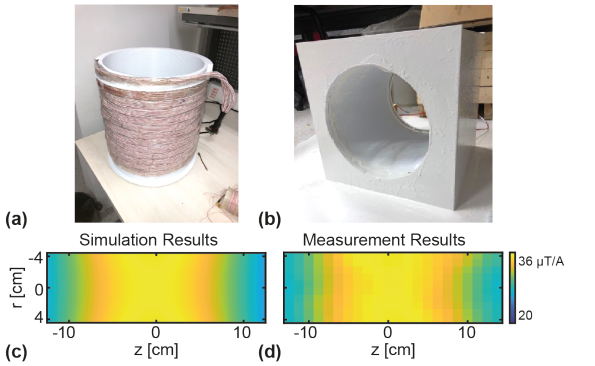

Figure 1: a) Magnetostimulation head coil with 30 cm inner diameter, and (b) its encased version. c) Simulated and (d) measured coil sensitivities in a 8×25 cm^2 around the coil center. The measured coil sensitivity was 37.4 μT/A, with greater than 95% homogeneity in an 11.0 cm-long region along the z-direction.

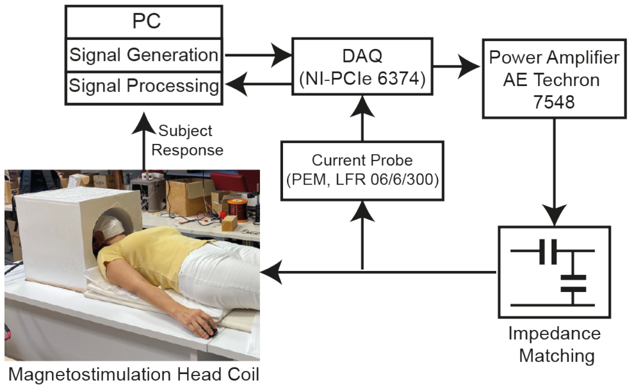

Figure 2: Flowchart of the magnetostimulation experiments conducted in the human head at 24 kHz. The amplitude of the pulses with 50 ms duration were controlled using a PC and a DAQ module. The subjects reported the stimulation response via a mouse click. A current probe was used for real-time measurement of the magnetic field amplitude.

Here, ΔB_{min} is the asymptotic threshold at high frequencies (approximately equal to the threshold around 25 kHz), r_{eff} is the effective radius of the body part, and $\lambda_{fit} \approx 285$ mT-pp·cm is a constant previously fitted using the magnetostimulation thresholds in the lower arm and lower leg [1]. Assuming $r_{eff} = 10$ cm for the human head yields $\Delta B_{min} = 28.5$ mT-pp.

Based on this computation, an initial target magnetic field is set as 35 mT-pp. To achieve this target, a standard solenoidal head coil would have voltages exceeding 30 kV at around 25 kHz. In our design [10], 12 Litz wires were twisted together to form a Rutherford cable. Then, a solenoidal head coil with an inner diameter of 30 cm was constructed with 13 turns of this cable. This head coil, shown in Fig. 1a-b, reduces the voltages at the targeted field to around 3 kV, thanks to its low inductance of 42.7 μH. The simulated and measured coil sensitivities are shown in Fig. 1c-d. The sensitivity measurements were performed using a Gaussmeter (Model 475 DSP Gaussmeter, Lake Shore Cryotronics, Inc), with its axial probe placed on a robot arm. The measured sensitivity at the center of the coil was 37.4 μT/A, with greater than 95% homogeneity in an 11 cm-long region along the z-direction.

II.II. Human Subject Experiments

This study was approved by the Ethics Boards of Hacettepe University and Bilkent University. Three healthy subjects (1 female, 2 males) with ages 26±1 were recruited after medical examination and screening for safety considerations. The experiment setup is shown in Fig. 2, where the pulse amplitudes were controlled via MATLAB using a DAQ module. The head coil was impedance matched to the power amplifier at 24 kHz. The pulse duration was set to 50 ms, as previous work has shown that the thresholds converge to a constant value for durations over 20 ms [5]. A Rogowski AC current probe was utilized for real-time measurement of the magnetic field in the coil.

Subjects placed their heads inside the head coil and were instructed to click a mouse button whenever they felt a nerve stimulation. The pulse amplitude was increased gradually at 4 s intervals, allowing the subjects sufficient time to report a stimulation. After the mouse click, the experiment was briefly paused and then restarted from a low field amplitude. This procedure was repeated 3 times to determine the PNS limits more accurately.

III. Results and Discussion

Figure 3 shows the magnetostimulation thresholds for 3 subjects, for all 3 repetitions. The mean threshold values across subjects are 7.98±2.20 mT-pp, 7.56±0.94 mT-pp, and 6.11±1.44 mT-pp for the first, second, and third repetitions, respectively. The mean threshold across all repetitions and subjects is 7.21±1.63 mT-pp. The subjects described the PNS sensation as follows: twitching around the cheekbone or the lips, tingling around the temples. These PNS locations are in line with our expectations from previous electric field simulations in the head [10].

As seen in Fig. 3b, the intersubject variation is the largest for the first repetition, which served as an introductory trial for the subjects to identify the nerve stimulation sensation. In addition, the intrasubject variation among the repetitions is the highest for the first repetition, as well. The subjects reported that recognizing the PNS sensation became easier after the first repetition, which caused the mean thresholds to decrease with the

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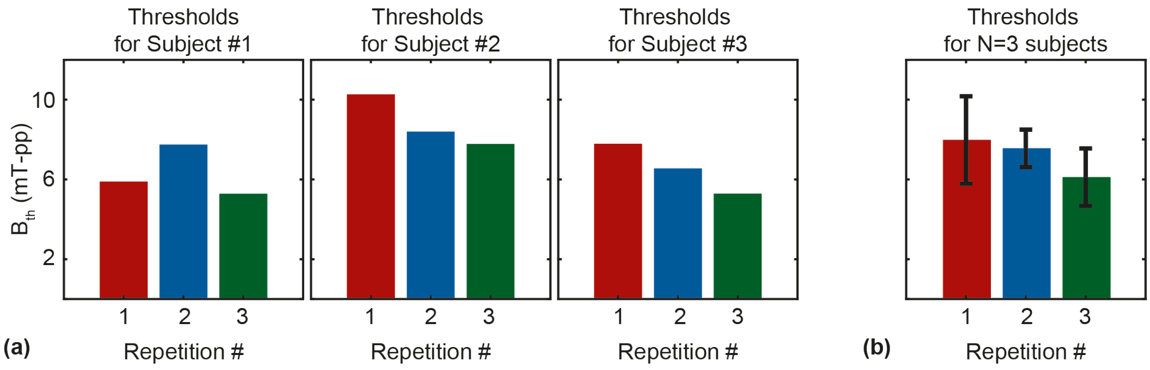

Figure 3: Magnetostimulation thresholds for 3 subjects. (a) Individual thresholds and (b) mean thresholds across 3 subjects, for 3 repetitions. Error bars in (b) denote the standard deviations across all subjects.

repetition number. If we omit the results from the first repetition, the mean threshold of the second and the third repetitions across all subjects is 6.84±1.35 mT-pp.

The magnetostimulation thresholds from these human subject experiments are considerably lower than the initially computed value of 28.5 mT-pp. This discrepancy potentially stems from the differences in the electrical properties of the tissues in the head versus the arm/leg, as well as the position/depth of the stimulated nerves with respect to electrical field patterns. Multiphysics simulations that take anatomical measures and electrical properties into account need to be performed to better understand these differences.

IV. Conclusion

This work presents the preliminary results of human subject magnetostimulation experiments for human-head size MPI systems. We plan to conduct human subject experiments with a larger cohort of subjects and perform detailed simulations to better understand the PNS limits in the head.

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Author's statement

Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

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