Experimental determination of human peripheral nerve stimulation thresholds in a 3-axis planar gradient system

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Introduction: Nerve stimulation has been reported to occur during MRI sequences where gradients are pushed to high strength and slew rate. This nerve stimulation occurs because the rapidly changing magnetic fields from the gradient coil induce an electric field that is experienced by the human subject; however, many details related to this effect are still under investigation. Nerve stimulation represents a limit on the strength and rise time of gradient pulse sequences, which in turn can limit image quality. In order to maximize gradient coil performance, a planar gradient coil capable of gradients of 250 mT/m/axis has been constructed[1]. The electric field induced by this coil were simulated and the peripheral nerve stimulation threshold curve was tested, and is here compared to other gradient coil threshold data. This is the first peripheral nerve stimulation data to be obtained for a planar gradient coil.

Method: An electric field simulation was performed using a finite difference method [2], the visible man human model, and the current element pattern for the flat gradient. The model was positioned with its centre 17.5 cm above the surface of the top gradient, and aligned in the x and z direction with the centre of the gradient. The gradients were simulated simultaneously on all 3 axes with a ramped current of 6283 A/s. This is equivalent to the maximum rate of change for a 1A (amplitude), 1kHz (frequency) sinusoid. The simulation result was compared to previously calculated electric field induced in a head gradient coil [3].

Human tests were also conducted. Healthy subjects were positioned supine and/or prone on the gradient coil with their waists approximately at the centre of the z-axis. A continuous pulse train was applied to all three axes simultaneously with a gradient amplitude of 138 mT/m/A, a zero- to-maximum rise time of 30μs, and a flat top time of 300 μs. The subject was asked to adjust his position until the sensation was maximized. Once the subject was positioned, the location and description of stimulation was recorded, along with the self-reported height, weight, and gender. To determine the stimulation threshold curve, a pulse sequence was then applied with pulse trains that ramped from 0 to maximum amplitude in 32 steps. At each step, a pulse train of 256 pulses rose from minimum to maximum gradient amplitude in a defined rise time, τ. The pulse train was applied 4 times at each step, with a repetition time of 1 second between applications. When the subject reported stimulation, the sequence was stopped, and the step number of the amplitude causing stimulation was recorded. This process was repeated for 6 to 10 threshold points at rise times ranging from 20 to 160μs. Rise times at the extreme ends of the detectable range were tested multiple times for consistency. The stimulation experiment was performed on 10 healthy subjects (8 male, 2 female). The threshold curves were plotted, and linear regression was applied to the data.

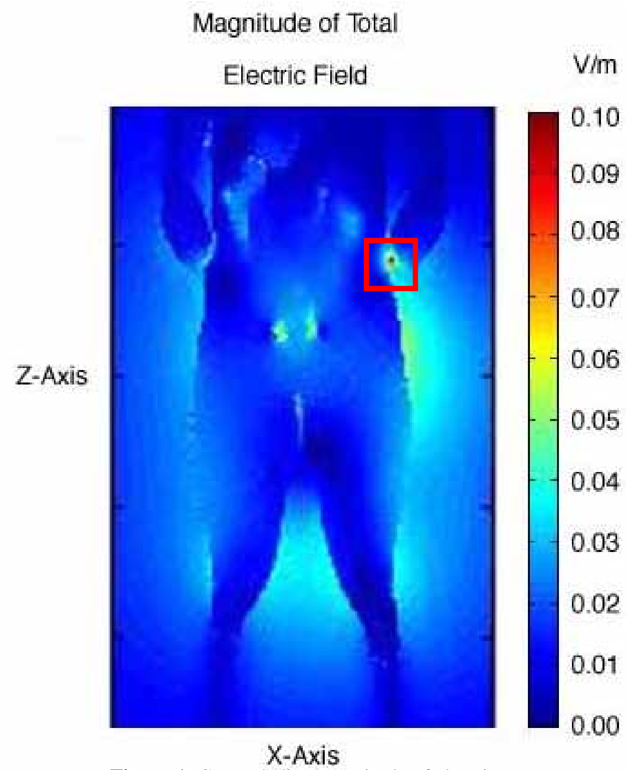

Figure 1: Coronal slice magnitude of electric field experienced on the planar gradient

Results: Figure 1 shows the total electric fields induced in a male model; the boxed region indicates the location of the maximum induced electric field. This maximum induced electric field was 0.25 [V/m], assuming 6238 A/s. Of the 10 subjects tested, 9 experienced maximum stimulation while supine and reported the stimulation as a muscle twitch or contraction either in the right rib cage or right lower abdomen. One subject experienced a tingling sensation while prone. Figure 2 shows the stimulation threshold curve in terms of ΔG (maximum gradient – minimum gradient) and τ for the planar gradient as well as a head gradient coil and a body gradient coil [4]. From the curve we calculated a ΔG_{min} of 95±5 mT/m and a slope, or SR_{min} of 280 ± 18 mT/m/ms. A ratio of these two terms leads to a calculation of the nerve parameter, chronaxie time: τ_c = 340 μs. Combining the location of stimulation with the electric field simulations we obtain a nerve rheobase value of E_r = 6.36 V/m.

Discussion/Conclusion: If the peripheral nerve stimulation threshold is related to the degree of electric field exposure, the threshold for both the head and the body gradient coil would be expected to be lower than the threshold for the planer coil. This is what we see. With the planar gradient coil we were able to obtain a significantly higher ΔG_{min} and a steeper SR_{min} than had been previously reported. The calculated τ_c = 340μs for the planar coil was lower than the τ_c of 904μs and 714μs determined from the threshold curves of the head and body gradient coils respectively[4]. While the reported E_r = 6.36 V/m is larger than some previous studies, it is similar to the 5-10 V/m expected when the scalar potential is taken into account [3].

The most important result from this investigation is that, compared to whole body gradient coils and previously reported head/neck gradient coils, the planar gradient coil set can be operated at significantly higher gradient strengths and slew rates before the onset of PNS in subjects. This further supports the hypothesis that customized gradient coils may represent the best approach to increasing gradient system performance in light of PNS limitations in human subjects.

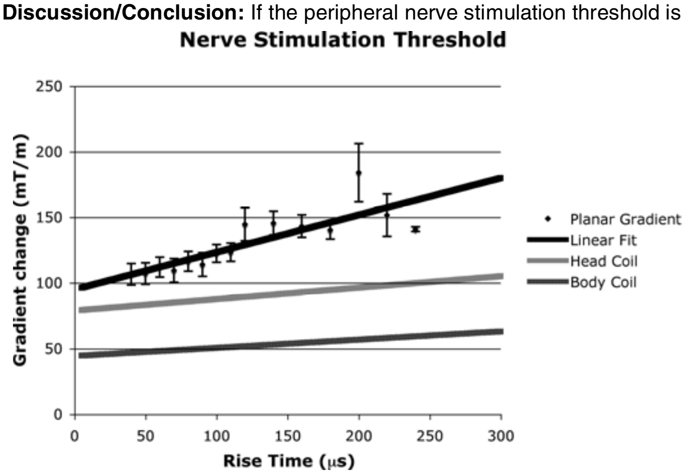

Figure 2: Chart of linear regression, nerve stimulation threshold compared to literature values for a body and head gradient coil.

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