Human nerve stimulation threshold determination in a planar gradient system

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Introduction: Peripheral nerve stimulation has been reported during MRI pulse sequences where gradients are pushed to high strength and slew rate. Stimulation occurs because changing magnetic fields, such as the rapid ramping of a gradient coil, induces electric fields that can trigger an action potential in a sensory or motor nerve; however, many of the details governing PNS, including the effect of the gradient coil wire pattern on the stimulation threshold variation, are still under investigation. Nerve stimulation represents a limit on gradient coil operation with a human subject. For safety reasons gradient strength and slew rate may not be increased beyond the point of pain, and this pulse sequence restriction can limit the quality of the final image. A planar gradient, shown in Figure 1, capable of X- and Y- axes gradient strengths of 250 mT/m/axis and Z-axis gradient strengths of 400 mT/m/axis has been constructed [1]. The peripheral nerve stimulation threshold curve was experimentally determined and analyzed by comparing the threshold that could be achieved using the planar gradient to those obtained for other gradient coils.

Figure 1: Subject supine on planar gradient

Methods: Subjects were positioned supine on the gradient coil with their waists approximately at the centre of the z-axis. A continuous trapezoidal pulse train was applied to the Z-axis with a gradient amplitude of 200 mT/m/A, a zero to maximum rise time of 170 µs, and a flat top time of 1000 µs. The subject was asked to adjust position until the sensation was maximized. The experiment consisted of 20 threshold determinations. For each point, a pulse sequence was used that consisted of 128 pulse trains applied at 1second intervals. Each pulse train contained 256 trapezoidal pulses that rose to their maximum amplitude in over a defined rise time (τ), held the maximum gradient strength for a flat top time of 1000µs, then decreased to zero amplitude in time τ. The amplitude of the pulses in the train rose from 0 to 400 mT/m/ms in 32 steps, with the amplitude of pulses remaining the same for 4 entire pulse trains before increasing to the next level. When the subject reported stimulation, the sequence was stopped and the level of amplitude causing stimulation was recorded. Rise times were varied between 10 and 1500 µs on 14 subjects (11 male, 3 female). The threshold points were used to determine individual threshold curves, and an average curve was calculated, using logistic regression for time points where not all the subjects stimulated. Finally, the location of the stimulation was recorded along with a description of the sensation and the subject's self-reported height, weight and gender.

An electric field simulation of the planar gradient was performed using a finite difference method [2]. The visible man human model was positioned to mimic the average position of the subjects in the study. The Z-axis was simulated with a ramped current of 6283 A/s, which is equivalent to the maximum rate of change of a 1A, 1 KHz, sinusoidal current. The simulation results were combined with the average SR_{min} (minimum slew rate, slope of the threshold curve) from the experiment to estimate nerve parameters. The results from both the experiment and the simulation were compared with previous stimulation experiments.

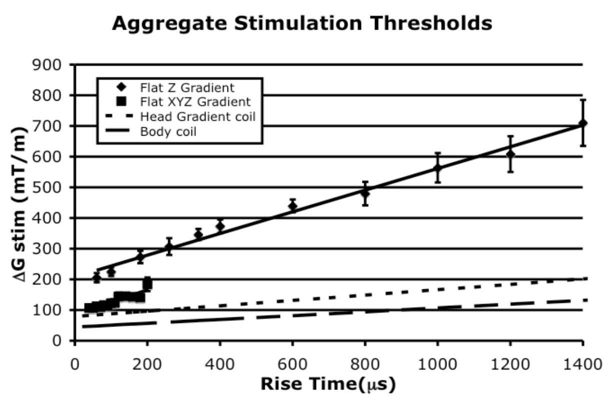

Figure 2: Nerve stimulation threshold for planar gradient, head gradient, and whole body gradient

Results: Figure 2 shows the stimulation threshold curve in terms of the change in gradient (ΔG) and time (τ) for the planar Z axis (ΔG_{min} of 208±17 mT/m, SR_{min} of 353 ± 46 mT/m/ms, τ_c = 590 ± 130 µs), all 3 axes simultaneously [3], a head coil, and a GE body coil [4]. Figure 3 shows the electric fields induced in a male model. The box region indicates the location of maximum induced stimulation. From the curve and the simulation we calculated a rheobase E_r = 8.8 ± 1.1 V/m. The simulation exhibits electric field hot spots at approximately (but not exactly) the location of primary stimulation in the subjects.

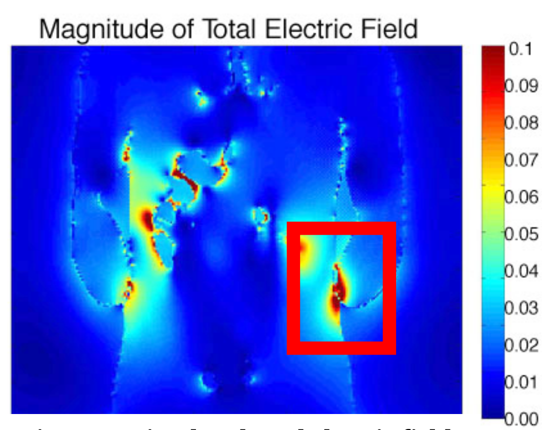

Figure 3: Simulated total electric field

Discussion and Conclusion: The calculated E_r = 8.8 V/m is higher than previous studies, but is consistent with the 5-10 V/m range suggested by theory. The chronaxie time is also similar to those reported in previous studies but higher than those reported for this coil when all three axes were run simultaneously. The planar gradients were able to achieve significantly higher ΔG_{min} and SR_{min} than had been reported for either the body or the head gradient coil. The threshold was also higher than the threshold for 3 simultaneous planar axes, suggesting that the Z gradient will not be the primary cause of stimulation for the planar gradients. This is the first time MRI gradients have exhibited PNS thresholds this high. The planar gradient can be operated at significantly higher gradient maxima and slew rates than other gradient coils without causing human stimulation.

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