

Peripheral nerve stimulation in MRI gradient coils

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In this seminar, we will review the basic features of peripheral nerve stimulation (PNS) as relevant to the operation of MRI gradient coils. We will discuss how the effect is manifested, the essential mechanism, the threshold equations, the main factors influencing thresholds, current regulatory status in various countries, and the most promising approaches to mediating the effect. Below is an introduction to the most important aspect of the seminar: the threshold equations for gradient PNS.

Put simply, PNS occurs during the operation of gradient systems because the alternating magnetic fields of the gradient coils induce electric fields in the body of the subject. These electric fields, if of sufficient magnitude and duration, can cause the excitation of the peripheral nervous system. Subjects typically report spatially localized sensations of pressure, tingling, or muscle twitching.

Any alternating magnetic field will result in induced electric fields, so the question arises: why do gradient coils induce this effect, while radiofrequency fields and the static fields of the main magnet do not? The answer is that gradient fields in MRI are typically operated such that they are switching at frequencies (~kHz) for which the human nervous system is particularly sensitive. RF fields are much too high frequency for the nervous system to respond. Patient movements through the static main fields are generally at frequencies that are too low.

A quantitative expression for PNS thresholds is as follows. It is known that human nerves exhibit an electric field excitation threshold that has the following phenomenological form:

$$E_{threshold} = E_r \cdot (1 + \tau_c / \tau)$$

where the left-hand side can be considered to be the average electric field to which the nerve is exposed, over a time τ . E_r (rheobase) is a constant equal to the minimum electric field required to cause stimulation, and τ_c (chronaxie time) is a time constant describing the approach of the threshold to the limiting value of the rheobase. For human peripheral nerves, E_r values are in the range of 5 - 20 V/m, while τ_c values are in the range of 50 - 800 μ s. The essential nature of the E-field threshold curve is that short electric field pulses need to be very strong in order to induce stimulation, while weak electric field pulses must be applied for a relatively long time.

The above electric field threshold curve can be translated into an equivalent magnetic gradient field threshold curve:

$$\Delta G_{threshold} = \Delta G_{min} + SR_{min} \cdot \tau$$

where $\Delta G_{threshold}$ is the change in gradient required to cause stimulation, and τ is the time over which the gradient field is switched. One critical observation is that there is a minimum change in gradient required to cause stimulation (ΔG_{min}), regardless of the gradient slew rate (slew rate is defined as dG/dt). Second, there is a minimum slew rate (SR_{min}) required for stimulation, regardless of the amplitude of the applied gradient. In particular, it must be emphasized that slew rate alone does not determine PNS thresholds. In many circumstances, it is possible to operate gradient systems at very high slew rates without inducing any effect. The ramifications of this threshold expression, which has been validated experimentally in many studies, will be a primary focus of the seminar.