PNS-Optimal Gradient Waveform Design

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Introduction

Switching magnetic field gradients can induce peripheral nerve stimulation (PNS) in patients, which is regulated for all human scans in a legally binding norm [1]. Modern MRI scanners with high-performance gradient systems have high maximum gradient strengths (gmax) and slewrates (smax). PNS can become a more dominating factor during gradient waveform design than gmax and smax. One approach to prevent PNS on clinical MRI scanners is to (globally) derate smax for the whole pulse sequence, hence increasing its overall duration.

The most accurate and least restrictive PNS model is the nerve response calculated through the convolution model [1]. However, using this model to derate smax globally leads to suboptimal trajectories in terms of minimal duration. Goal of the current work was to include the PNS convolution model already into the design of the gradient waveform, hence derating smax only where necessary. This leads to a time-varying smax instead of a constant global one. The approach was demonstrated for both spiral and Cartesian echo-planar imaging (EPI) trajectories.

Methods

The overall nerve response $R(t)$ along a single gradient axis is given by a convolution of slewrate $SR(t)$ with the individual responses [1]

$$R_{x,y,z}(t) = \frac{\alpha}{r}\int_0^t \frac{SR_{x,y,z}(\theta)c}{(c+t-\theta)^2}d\theta \qquad \text{Eq. 1}$$

where α denotes the effective coil length, r the rheobase and c the chronaxie time constant. These latter three scanner parameters are determined for each gradient coil model by the respective MRI manufacturers; in case of the 3T whole-body scanner MR750 (GE Healthcare, Milwaukee, WI, USA): α=0.333m, r=23.4T/s, c=334µs. The overall PNS threshold in % is given by $P_{thresh} = 100\sqrt{R_x^2 + R_y^2 + R_z^2}$. The permissible maximum is P_{thresh}=80% for normal and 100% for first and second controlled mode.

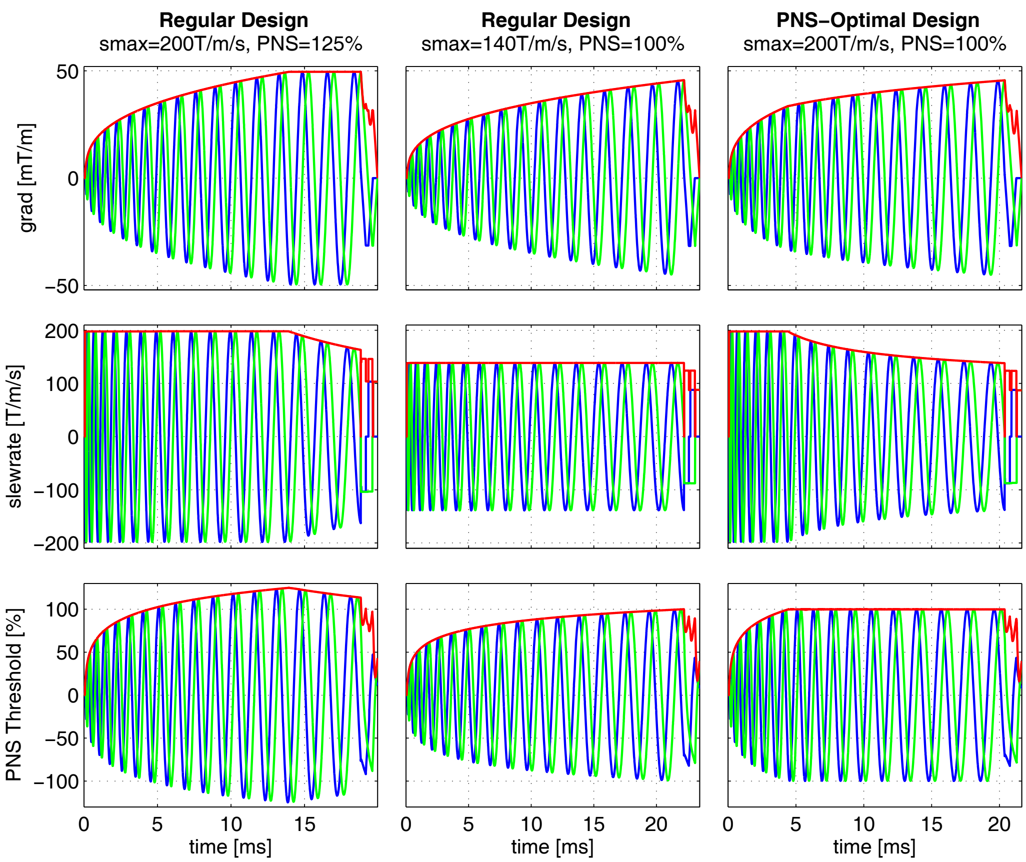
The spiral trajectory design is based on the Stanford *VDS* routines [2], starting with a smax-limited regime followed potentially by a gmax-limited regime [2]. The design traverses k-space step-by-step, determining the gradient waveform parameters dependent on smax and gmax. In this work, a time dependent smax(t) is introduced. The PNS threshold (Eq. 1) was calculated during each time step; if it exceeds the threshold, smax(t) is derated for this and the following time steps. To demonstrate the concept and investigate savings in the duration, exemplary spiral trajectories were designed using the following parameters: FOV=100mm, mtx=128x128, 4 interleaves, gmax=50mT/m, smax=200T/m/s (physical gradient limits of the MR750).

For the EPI trajectory, only ramps and blips introduce PNS, while it recovers during the constant time of the trapezoids. Introducing a time-varying smax has the additional constraint that the first moment of the ramps must be nulled (i.e., maintain equal areas), hence the ramps have to be symmetric. A suitable function proved to be tanh, where its width was optimised. To demonstrate the concept, a single-shot EPI trajectory with FOV=100, mtx=64x64, gmax=50mT/m, smax=200T/m/s was designed. All routines were implemented in Matlab (The MathWorks, Natick, MA, USA).

Results and Discussion

It is possible to shorten the spiral arm duration with the PNS-optimal design (see Fig. 1). The spiral arm durations were 18.77ms, 22.14ms and 20.32ms for the regular design with smax=200T/m/s (P_{thresh}=125%), smax=140T/m/s (P_{thresh}=100%) and a PNS-optimal design with P_{thresh}=100%, respectively. Similar savings of 8-10% in duration were found for P_{thresh}=80%, and also for spirals with 2 or 16 interleaves.

The savings for the EPI trajectory were less significant. For the regular design with smax=200 and 101T/m/s, the EPI durations were 52.25ms (P_{thresh}=153%) and 83.85ms (P_{thresh}=100%), respectively; for the PNS-optimal design with P_{thresh}=100%, the duration was 81.77ms. Similar savings in the range of 2-3% were also observed for P_{thresh}=80%. This relatively small reduction is probably due to the fact that the ramps are symmetric and time is lost during the first half of the ramp.



In summary, it is possible to shorten the duration of trajectories with a PNS-optimal design as compared to derating smax globally. PNS is often a neglected aspect in research sequences, partially because the literature [1] is not readily available. Hence, educating researchers and raising awareness in the community is similarly important.

References

[1] IEC 60-601-2-33;2010. Section 201.12.4.102

[2] BA Hargreaves, PhD thesis, Stanford, 2001; http://www-mrsrl.stanford.edu/~brian/vdspiral/

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Fig. 1: Exemplary spiral trajectories with gradient waveforms (top), its slewrate (middle) and the PNS curve (bottom); blue=x-axis, green=y-axis, red=$\sqrt{x^2+y^2}$. The left and middle columns show the regular design with smax=200 and 140T/m/s, respectively, while the PNS-optimal design is depicted on the right. In the PNS curve it can be seen that P_{thresh} is evenly distributed, hence optimally utilising this predominant limitation.