SAR sensitivity to phase andSAR sensitivity to phase and amplitude perturbations when utilizing parallel transmission

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Introduction:
When using parallel transmission at high field, it is well established that high local specific absorption rate (SAR) values can occur [1]. A conservative approach to guarantee patient safety can be provided by using the worst-case scenario to derive the limits to be enforced by the SAR monitor [2]. This approach significantly limits the in-vivo applications of parallel transmission at high field. More advanced solutions have been proposed to allow more power while guaranteeing patient safety [3]. Knowledge of the SAR under different conditions is vital for the design of such less restrictive SAR monitors. In the recent past, studies have investigated the variability in SAR by comparing various pulse designs and design methods [4,5]. However, no reports have been made regarding the behavior of transmit-SENSE [6] pulses with regard to amplitude and phase perturbations. In this work, we investigated the behavior of the local SAR regarding perturbed spoke k-space trajectory based excitation pulses [7] designed using simulated field maps.

Methods:
Simulations of an eight-anatomical structure human head model (Aarkid, East Lothian, Scotland) placed in the centre of a transmit array were performed using the finite element method (HFSS, Ansoft, Pittsburgh, PA). The transmit array used in this study consists of 8 stripline dipoles distributed every 40-degrees on a cylindrical surface of 27.6-cm diameter, leaving an open space in front of the patient's eyes. Tuning (297Mhz), matching (50-Ohm) and mutual coupling were taken into account (Fig 1,A). Spoke like pulses [7] were designed [8] for flip-angle homogenization (20°) in a central slice of the brain. Perturbations were introduced by multiplying the spokes coefficients by random complex values. Limiting the range of the random factors, the size of the sampled space was varied up to ±40% in amplitude and ±144° in phase (minimum step size 0.1% in amplitude and 0.36° in phase). For every subspace with fixed amplitude and phase, 20.10^3 samples were considered, i.e. a total of $0.93.10^6$ perturbed pulses were analyzed in this study. Relative changes in SAR were analyzed using SAR_p/SAR_r ratio, where SAR_p and SAR_r are the maximum 10-gram SAR normalized to the total power in the perturbed and reference pulse, respectively. For comparison, the equivalent N-Spoke worst-case SAR (SAR_m) values were calculated [9]. All SAR calculations were implemented in CUDA and performed on a GPU (GeForce® 9600, NVIDIA®).

Results:
Introducing random perturbations of up to ±144° in phase only, the SAR_p/SAR_r remained under 1.65 (Table A-C). Including amplitude perturbations of up to 40%, the SAR_p/SAR_r (Table A-C) was found to increase by up to a factor of 3.1. Outside the sampled subspaces, the worst case SAR_m/SAR_r (Fig. 1 D) was found to be 7.1, 9.60, and 9.44 for the 2-, 3-, and 5-Spoke pulse, respectively.

Amplitude \ phase	±0°	±36°	±72°	±108°	±144°
±0%	1.	1.11	1.23	1.33	1.42
±10%	1.2	1.27	1.35	1.47	1.56
±20%	1.43	1.53	1.52	1.64	1.75
±30%	1.66	1.68	1.88	1.89	1.97
±40%	1.99	2.12	2.18	2.33	2.46

Table A: The maximum normalized SAR_p/SAR_r for a 2-spoke pulse.

Amplitude \ phase	±0°	±36°	±72°	±108°	±144°
±0%	1.	1.21	1.37	1.54	1.65
±10%	1.25	1.36	1.51	1.7	1.86
±20%	1.58	1.61	1.77	1.98	2.23
±30%	1.86	2.1	2.28	2.24	2.55
±40%	2.39	2.38	2.75	2.9	3.1

Table B: The maximum normalized SAR_p/SAR_r for a 3-spoke pulse.

Amplitude \ phase	±0°	±36°	±72°	±108°	±144°
±0%	1.	1.15	1.27	1.41	1.51
±10%	1.32	1.38	1.47	1.61	1.72
±20%	1.68	1.77	1.86	1.88	2.12
±30%	2.09	2.31	2.23	2.37	2.4
±40%	2.6	2.7	2.94	2.95	2.98

Table C: The maximum normalized SAR_p/SAR_r for a 5-spoke pulse.

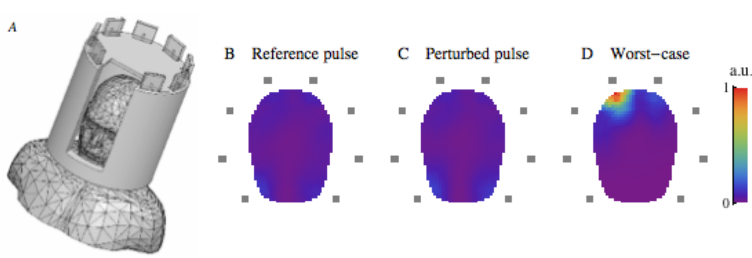

Figure 1: Simulation model, and axial slices containing the peak 10-gram SAR for a 3-spoke pulse. Coil positions are indicated with gray squares. A: Coil model as used in the simulations. B: SAR_r distribution obtained using the reference pulse. C: the maximum SAR_p found by introducing up to 20% amplitude perturbations and 20° in phase. D: the worst-case local SAR.

Discussion and conclusions:

When considering only a limited subspace of perturbations around a nominal pulse design, the highest local SAR remains reasonably stable. Aside from amplitude perturbations, the maximum SAR_p/SAR_r remained under 1.65 in contrast to the 9.60 SAR_m/SAR_r found considering the complete space. Including amplitude perturbations up to 40%, a maximum SAR_p/SAR_r of 3.10 was found. This clearly illustrates the minor effect phase variations have on the local SAR in this setup. This may not be the case for other coil designs, in particular if coil elements are located at a more distant radius; then the effect of combined modes on local SAR may be more pronounced towards the center of the head. Nevertheless, in order to achieve a SAR increase comparable to the worst-case SAR_m/SAR_r (Fig. 1), extremely large amplitude perturbations are needed. These results indicate that although substantial variations can occur around a nominal pulse design, the peak local SAR may be considered relatively robust, and remains far below the local SAR obtained in the worst-case scenario. This motivates focusing on power limitation rather than phase restriction for SAR-monitoring systems using the described setup.

References:
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