# SAR Reduction in Parallel Transmission by Allowing Spatial Phase Variation

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**Introduction** Using multiple coils for transmission, RF pulse duration and/or specific absorption rate (SAR) can be reduced [1,2]. On the other hand, in the SAR reduction method developed in [1], SAR of shortened pulses can not be reduced significantly. In this work an SAR optimization method based on releasing phase constraints of excitation samples is developed. The new method is developed for pulses designed based on small-angle approximation. This method benefits the fact that phase variations causes less error in the final image than magnitude variations (i.e. there is a higher degree of freedom in phase variations). This method allows minimization of SAR in time reduced pulses (time reduction factor (*R*) up to number of coils). Phase optimization problem is non-convex, therefore a search algorithm, particle swarm optimization (PSO), is used [4]. The method is tested with electromagnetic simulations of a 6-Coil configuration. Effect of phase variations on excitation error is tested with Bloch simulations. Impact of magnitude variations on SAR is also tested.

**Methods** Formulation developed in [5] is used for calculation of current waveforms. Formulation uses small-angle approximation and it is very similar to Transmit SENSE [2]. Relation between current waveforms and desired excitation profile is given by

$$\boldsymbol{m} = \boldsymbol{Ab} \tag{1}$$

where $\boldsymbol{m}$ is a Mx1 column vector that contains the desired magnetization values of the corresponding samples from region of interest and $\boldsymbol{b}$ is a column vector that contains the current samples of all coils. Size of vector $\boldsymbol{b}$ is (M/R)x1 where R is the time reduction factor. (M/R)xM size $\boldsymbol{A}$ matrix consists of the sensitivity profiles of coils and k-space trajectory samples. Relation between the current samples and the whole-body SAR is given by the following formula

$$\mathrm{SAR}_1 = \boldsymbol{b}^{\boldsymbol{H}} \boldsymbol{Rb} \tag{2}$$

where $^{\boldsymbol{H}}$ is the conjugate transpose operator. $\boldsymbol{R}$ is a (NM/R)x(NM/R) size matrix that contains E-field cross integrals of the transmit coils. Since $\boldsymbol{A}$ is underdetermined (i.e. $\boldsymbol{A}$ has a nullspace), $\boldsymbol{b}$ that minimizes (2) subjected to (1) is given by the following formula:

$$\boldsymbol{b_{opt}} = (\boldsymbol{R}^{-1}\boldsymbol{A^H})(\boldsymbol{AR}^{-1}\boldsymbol{A^H})^{-1}\boldsymbol{m}, \tag{3}$$

$$\mathrm{SAR} = \boldsymbol{b_{opt}^H R b_{opt}}. \tag{4}$$

In [4], SAR is optimized by assigning a fixed value to the 2-norm of the difference between the desired excitation profile and the modified excitation profile. In this work, phases and magnitudes of elements of $\boldsymbol{m}$ are varied using the PSO search algorithm to reduce SAR value given in (4). Phase variations and magnitude variations are treated separately because their effects on the final image are different. There exists higher degree of freedom in phase than magnitude. Since optimization problem under consideration is non-convex, the PSO search algorithm is used. To analyze the effect of magnetization profile modification on the excitation error, Bloch simulations are performed. Each sample pixel in the excitation space is divided into sub-pixels. Total magnetization of each pixel in the region of interest is calculated by summation of sub-pixels of the corresponding pixel. Excitation error is given by the following formula.

$$\mathrm{Error} = \left\| |\boldsymbol{m_f}| - |\boldsymbol{m}| \right\|_2 / \|\boldsymbol{m}\|_2 \tag{5}$$

Here, $|.|$ operator takes magnitude of each element of the vector associated with it. $\|.\|_2$ is the 2-norm operator. $\boldsymbol{m_f}$ is the Mx1 vector that contains final magnetization value of each pixel which are calculated by summation of magnetization values of sub-pixels. In excitation error defined in [4], absolute value of the excitation samples is not taken. Here, absolute value differences are used for taking higher amount of phase variations into account. Signal losses caused by phase variations are considered by sub-pixel summations. Phase of each excitation sample is forced to be in 0-60 degrees interval to prevent signal losses. Excitation error is calculated for both optimal excitation profile and the uniform phase excitation profile.

**Simulations** Method is tested with 2D excitation pulses for 3T. 42x42cm$^2$ FOV is sampled to 32x32 pixels. "Don't-care" care regions are assigned to the outside of the phantom. SAR reduction for time reduction factors from 1 to 5 are tested where cartesian k-space trajectory is used for all cases. A cylindrical phantom was used where the diameter, length conductivity and relative permittivity values were 40cm, 40cm, 0.68 s/m and 70, respectively. 6 rectangular coils were placed around the phantom. Sensitivities and E-field cross integrals of the coils were obtained by electromagnetic simulations. In the PSO algorithm, phase search was forced to remain in 0-60 degrees interval for each pixel. Magnitude variation was forced to 0.9-1.1 interval. Parameters used for PSO algorithm were as follows: number of particles = 20, dt = 1, K = 0.729, $\phi_1$ = 2.8, $\phi_2$ = 1.3 (Parameter names are identical to the parameters in [4]).Tilt angle of 90 degrees were used for all cases. For excitation error analyses, each pixel in the FOV is divided into 25 sub-pixels. In Bloch simulations, magnetizations of sub pixels are calculated.

**Results** Results in Table 1 show that with high time reduction factors, phase optimization method performs better. Method gave no SAR improvement for time reduction factors of 1 and 2, however, SAR improvement is more crucial in excitations with high time reduction factor. Using magnitude variation alone or together with phase variation did not introduce notable improvement over phase optimization. Bloch simulations show that excitation distortion caused by phase-magnitude variations were not significant. When phase search was not forced to 0-60 degrees interval (Table 2), there was significant change in the SAR improvement only for time reduction of 3. This shows that high SAR reduction can be obtained even when signal losses caused by rapid phase changes are prevented.

**Conclusions** A new SAR optimization method for parallel excitation is explained. Method relies on the fact that phase variations in the excitation profile do not cause significant image degradation. Benefiting the freedom in phase variations resulted in SAR reductions up to %57. Excitation profile error caused by spatial phase variations was not significant (Table 1). The new method gave better SAR improvements for higher time reduction factors. This is important because method developed in [1] becomes less effective in higher reduction factors. When phases are not forced to 0-60 degrees interval, there was a higher SAR improvement for time reduction factor of 3 but excitation error was also higher. This problem can be solved by using a constraint search algorithm where the constraint will be the signal loss being less than a critical value.

| Time Reduction | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| (%) SAR reduction | 0 | 9 | 18 | 36 | 57 |
| OP Error | 0.23 | 0.245 | 0.31 | 0.32 | 0.32 |
| UP Error | 0.23 | 0.23 | 0.32 | 0.32 | 0.3 |

**Table 1** Results when phase search is limited to 0-60 Degrees interval. Excitation error values for optimal phase (OP) and uniform phase (UP) excitations are given

| Time Reduction | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| (%) SAR reduction | 0 | 13 | 46 | 39 | 57 |
| OP Error | 0.23 | 0.23 | 0.53 | 0.33 | 0.32 |
| UP Error | 0.23 | 0.32 | 0.32 | 0.3 | 0.3 |

**Table 2** Results when there is no constraint imposed on the phase search interval. Excitation error values for uniform phase (UP) excitation and optimal phase (OP) excitation are given

**References** [1] Zhu Y. (2004) MRM 51:775-784 [2] Katscher U et al, (2003) MRM 49:144-150 [3] I. Graesslin et al, ISMRM (2008) 621 [4] J. Robinson et al, IEEE Transactions on antennas and propagation, Vol. 52, No. 2, p. 397-407 2004 [5] Grissom W et al, A new method for the design of RF pulses in Transmit SENSE, Proceedings of the 2nd International Workshop on Parallel Imaging. Zurich Switzerland 2004. p. 95