

# PTx pulse design with explicit hard constraints on local and global SAR and maximum and average forward power

Bastien Guerin<sup>1</sup>, Matthias Gebhardt<sup>2</sup>, Elfar Adalsteinsson<sup>3,4</sup>, and Lawrence L. Wald<sup>1,4</sup>

<sup>1</sup>Martinos Center for Biomedical Imaging, Dept. of Radiology, Massachusetts General Hospital, Charlestown, MA, United States, <sup>2</sup>Siemens Healthcare, Erlangen, Germany, <sup>3</sup>Dept of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, MA, United States, <sup>4</sup>Harvard-MIT Division of Health Sciences Technology, Cambridge, MA, United States

**Introduction:** PTx pulse design is usually performed while continuously regularizing average forward power to penalize large voltage increases that only marginally improve spatial fidelity [1]. Electromagnetic (EM) simulations have shown however that this strategy does not control local SAR [2]. In this work, we propose two small-tip-angle pulse design algorithms that explicitly and jointly constrain spatial fidelity, local SAR, global SAR as well as average and maximum forward power. Our approach is similar to [3] but is not limited to quadratic cost functions and constraints, which could prove useful for incorporation of arbitrary constraints protecting hardware components in the transmit chain. Moreover we use these algorithms in conjunction with an approach compressing the local SAR matrices [4] making it possible to design 2-spoke pTx pulses with local and global SAR constraints within 15 secs.

**Methods:** We solve the following small flip angle excitation pulse design problem (pb. #1):  $\min_{\mathbf{x}} \|\mathbf{Ax} - \mathbf{b}\|_2^2$  s.t. a)  $\|\mathbf{x}\|_2^2/50 \leq P_{\max}^{\text{aver}}$ ; b)  $\|\mathbf{x}\|_{\infty}/50 \leq P_{\max}^{\text{peak}}$ ; c)  $\mathbf{xS}_n\mathbf{x}^H \leq S_{\max}^{\text{local}} \forall n$  and d)  $\mathbf{x}(\mathbf{S})\mathbf{x}^H \leq S_{\max}^{\text{global}}$ , where  $\mathbf{A}$  is the gradient matrix,  $\mathbf{x}$  is the pulse,  $\mathbf{b}$  is the complex target excitation profile,  $\mathbf{S}_n$  are the local SAR matrices,  $\mathbf{S}$  is the global SAR matrix,  $P_{\max}^{\text{aver}}/P_{\max}^{\text{peak}}$  and  $S_{\max}^{\text{global}}/S_{\max}^{\text{local}}$  are the average/peak power and global/local SAR limits. In order to reduce computation time, we compress the full set of 10g local SAR matrices in the body to a smaller set of Virtual Observation Points (VOPs) [4]. We solve pb. #1 using an interior point constrained optimization algorithm which directly enforces the constraints (a)-(d) and does not depend on a tradeoff free parameter (regularization) that must be determined by the user [5]. We also solve an equivalent problem (pb. #2):  $\min_{\gamma} \{\max_n \mathbf{xS}_n\mathbf{x}^H\}$  s.t. a)  $\|\mathbf{x}\|_2^2/50 \leq P_{\max}^{\text{aver}}$ ; b)  $\|\mathbf{x}\|_{\infty}/50 \leq P_{\max}^{\text{peak}}$ ; c)  $\|\mathbf{Ax} - \mathbf{b}\|_2^2 \leq \epsilon$  and d)  $\mathbf{x}(\mathbf{S})\mathbf{x}^H \leq S_{\max}^{\text{global}}$ , using the same interior point algorithm by noting that  $\min_{\gamma} \{\max_n \mathbf{xS}_n\mathbf{x}^H\} \Leftrightarrow \min_{\gamma} \gamma$  s.t.  $\gamma \geq \mathbf{xS}_n\mathbf{x}^H \forall n$ . Pbs. #1 and #2 are both convex and equivalent, i.e. they yield the same local SAR versus fidelity tradeoff, and are complementary ways of solving the pulse design problem. We evaluated these approaches using FDTD simulations (SEMCAD, SPEAG, Zurich) of the realistic, 77 tissue types, 1mm resolution Virtual Family "Duke" body model (IT'IS Foundation, Zurich) [6] and an 8 chns. 3T pTx body array (no coupling modeled). RF shimming and 2 spokes pulses were designed that attempted creating a uniform 10° flip angle excitation for a transverse slice at z=0cm.

**Results:** The VOP algorithm was run with a maximum SAR overestimation of 1%, yielding 775 VOPs (comp. factor=436). Fig. 1 shows L-curves quantifying the tradeoff between 10g local SAR, global SAR, max. and average forward power versus excitation fidelity for a 2 spokes excitation, obtained by varying both the local and global SAR constraints (pb. #1). These L-curves show the non-trivial correspondence between SAR and power metrics, and therefore the need for explicit local SAR control in pTx pulse design. They also show the capability of the algorithm to incorporate multiple constraints without a tradeoff free parameter, giving more flexibility to the operator to quickly explore the pulse design parameter space. Fig. 2 confirms that pbs. #1 and #2 are equivalent; these two complementary algorithms can therefore be used by the scanner operator to evaluate in real time the cost of decreasing excitation error (local SAR) in term of local SAR (excitation error).

## References:

- [1] Setsompop, K. (2008). *MRM* **60**(6): 1422-1432.
- [2] Wu, X. (2010). *Jour. Mag. Res.* **205**(1): 161-170.
- [3] Brunner, D. O. (2010). *MRM* **63**(5): 1280-1291.

- [4] Eichfelder, G. (2011). *MRM* **66**(5): 1468-1476.

- [5] Boyd, S. P. (2004). *Convex optimization*, Cambridge University Press.

- [6] Christ, A. (2010). *Phys. Med. Biol.* **55**: N23.

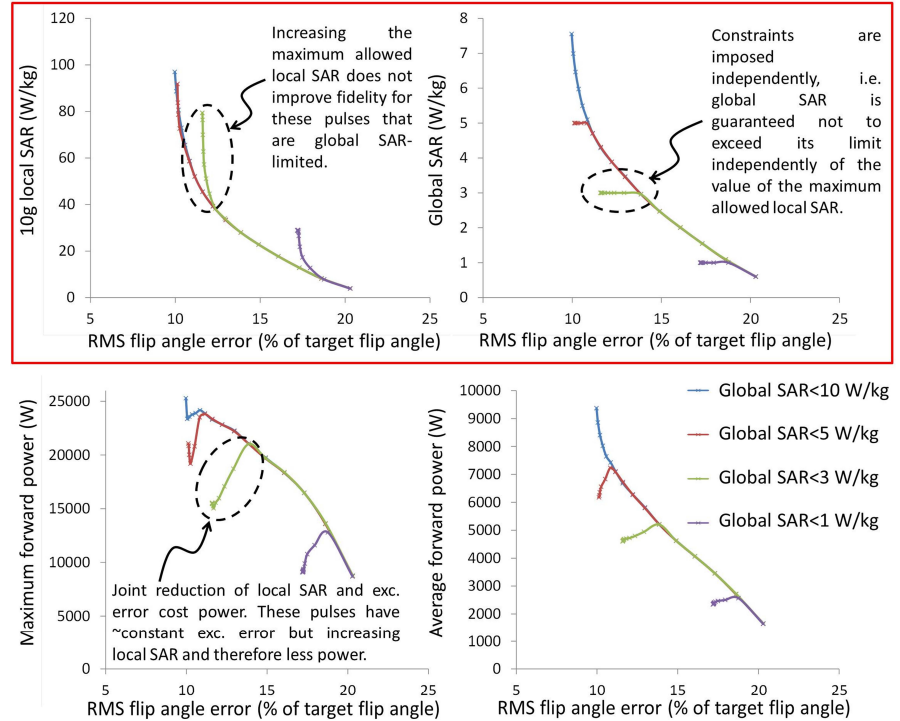


Fig. 1. L-curves quantifying the tradeoff between local and global SAR and max. and average forward power versus excitation error. Only local and global SAR were explicitly controlled (red box, max. and average forward power constraints were set to large values).

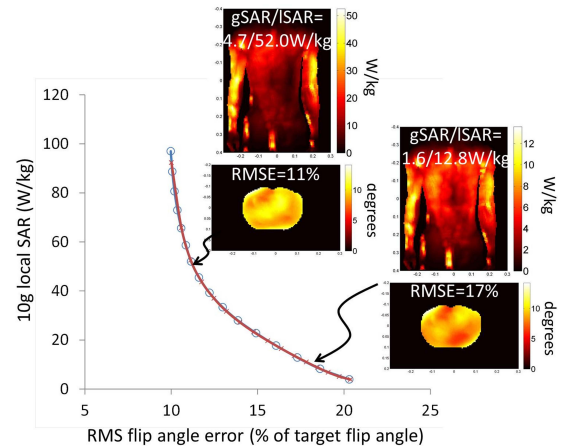


Fig. 2. L-curves showing the tradeoff between 10g local SAR and excitation error obtained by solving optimization pbs. #1 (blue line and circles) and #2 (red line and crosses).