Direct control of the temperature rise in parallel transmission via temperature virtual observation points: simulations at 10.5 T

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Purpose: Although it seems that there is a general consensus that temperature is the true relevant safety parameter, tracking the SAR in MR exams and in RF pulse design has remained the gold standard. As RF coil technology, static field intensity and temperature guidelines evolved throughout the years, SAR thresholds on the other hand have pretty much remained identical. A pulse design algorithm utilizing pTx was presented[1] where the absolute temperature guidelines were met by adjusting the SAR constraints in a feedback-based manner, while achieving better RF pulse performance. Absolute temperature guidelines however involve hardly controllable factors occurring in the patient's life (stress, weather, physical activity, fever etc) and thus appear less practical than temperature rise constraints. As a result, here we report a pTx RF pulse design under strict temperature *rise* constraints. The latter are directly enforced by using an equivalent SAR virtual observation point (VOP) model[2], this time based on temperature that we shall name T(Temperature)VOPs. Simulations are performed at 10.5 T with a 16 channels coil on the Duke head model of the virtual family, and with Time-Of-Flight (TOF) sequences of various durations.

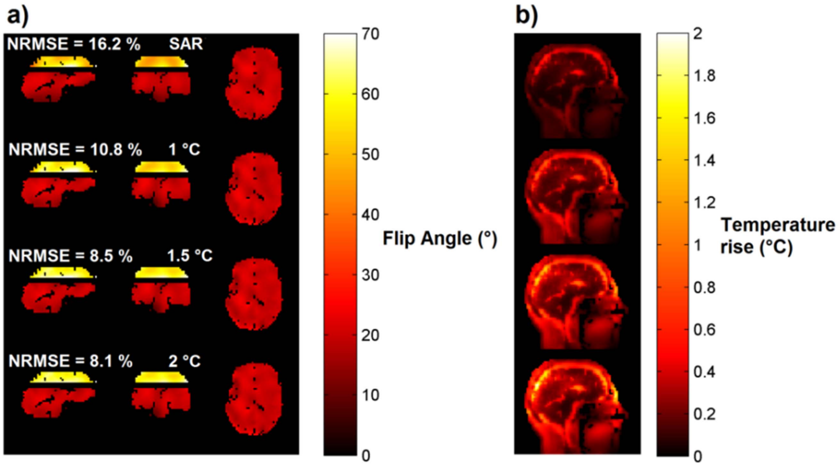
Methods: FDTD simulations were performed using Semcad X (Speag, Zurich, Switzerland) with a 16 channels transceiver coil, tuned and matched at 450 MHz, which corresponds to the Larmor frequency at 10.5 T. Magnetic and electric field maps were exported on a 4×4×4 mm^3 grid for pTx RF pulse design performed with Matlab (The Mathworks, Natick, MA, USA). The voxel-wise and 10-g SAR $\mathbf{Q(r)}$ matrices were then calculated. To build a compressed model of temperature rise constraints, pre-simulations were first conducted by integrating Pennes' bio-heat equation for each $\mathbf{Q_{ij}(r)}$ spatial distribution to give a corresponding temperature rise $\mathbf{T_{ij}(r)}$ term: $\rho c_p \frac{\partial T_{ij}(r)}{\partial t} = \vec{\nabla}.\left(k\vec{\nabla}T_{ij}(r)\right) - BT_{ij}(r) + \rho Q_{ij}(r)$, where ρ, c_p, k, B are the density, specific heat capacity, thermal conductivity and perfusion tissue-dependent terms respectively. The i and j labels respectively indicate the row and column numbers in the corresponding matrices. The SAR being given by a linear combination of the $\mathbf{Q_{ij}(r)}$ terms for an arbitrary RF pulse, the temperature rise can be quickly calculated via the same linear combination of the $\mathbf{T_{ij}(r)}$ pre-computed results[3] by exploiting the linearity of the thermal model. Thus, while SAR calculations can be conveniently calculated by using $\mathbf{Q}$ matrices, likewise the temperature rise can be calculated using $\mathbf{T}$ matrices and a corresponding (T)VOPs model can follow[2] (one for each sequence duration): $\exists i \in \text{TVOPs} \,/\, T_i \le \max\left(T(r)\right) \le T_i + \lambda T_G$, where e.g. the tolerance can be expressed in terms of the average temperature rise over the full model. Armed with these $\mathbf{T}$ matrices and TVOPs, thus one can solve the magnitude least squares pulse optimization under hard temperature rise constraints. The selected method in this work is the active-set algorithm because of its demonstrated success to tackle this specific nonlinear problem under hard SAR constraints[4]. The targets for this TOF illustration at 10.5 T are a 60° saturation pulse for a slab located at the top of the brain and a 20° pulse for a thicker and centered slab[5]. The slab-selective pulses use 3 and 2 k_T-points[6] trajectories respectively and are played back to back. The pulse design algorithm under strict temperature rise constraints becomes:

$$\min_{\mathbf{x}} f(\mathbf{x}) = \left\| \left| \begin{bmatrix} \mathbf{A_T} & 0 \\ 0 & \mathbf{A_B} \end{bmatrix} \mathbf{x} \right| - \begin{bmatrix} \boldsymbol{\theta}_\mathbf{T} \\ \boldsymbol{\theta}_\mathbf{B} \end{bmatrix} \right\|_2^2, \quad \text{s.t.}\ \ c_i(\mathbf{x}) \le T_{\max}\ (i = 1, \ldots, N_{TVOPs}),\ c_{pk}(\mathbf{x_k}) = |x_k|^2 \le 2\ \text{kW}\ (k = 1 \ldots N_c N_{kT})$$

, where $\mathbf{c_i}$, $\mathbf{c_{pk}}$, N_{TVOPs}, N_c and N_{kT} denote the temperature rise values over the TVOPs, the instantaneous power, the number of TVOPs, the number of channels and the total number of k_T points respectively. The matrices $\mathbf{A_T}$ and $\mathbf{A_B}$encode in the two slabs the spins'dynamics in the linear regime, while $\boldsymbol{\theta}_\mathbf{T}$ and $\boldsymbol{\theta}_\mathbf{B}$ are the corresponding target flip angles. The algorithm was tested for different sequence durations (6, 10 and 30 min) as well as with different maximum temperature rise constraints (1, 1.5 and 2 °C). Finally, the same algorithm was tried under the strict SAR constraints[4] issued by the IEC in order to compare RF pulse performance and safety.

Results: Fig. 1 provides the flip angle maps (a) with corresponding temperature rises (b) for the 6 min TOF sequence, and for the different constraints enforced. While the target flip angles can hardly be achieved mainly in the top slab and in the cerebellum with the SAR-constraint pulse design, very good excitation fidelity is obtained for the temperature-constraint pulse design as the temperature threshold is progressively increased. CPU time was on the order of 30 s with a standard desktop PC and for the investigated 16 channels coil (vs. 10 s for 8 channels). For all the considered sequence durations, the pulse design with 1 °C temperature rise constraint already outperformed the one under strict SAR constraints, yielding normalized root mean square errors (NRMSE) of 10.8, 12.6 and 15.5 % for the 6, 10 and 30 min sequences respectively, whereas 16.2 % was returned for the SAR-constrained pulse leading to temperature rises equal to 0.91, 1.10 and 1.37 °C. The thermo-regulated pulses become more and more advantageous as the temperature constraint is relaxed, 1.5 °C and 2 °C constraints leading respectively to 8.5 and 8.1 % NRMSEs for the 6 min sequence. The approach proposed here thus appears to be both more powerful due to smaller NRMSEs, but also safer as simulations show that a peak 10-g SAR equal to 10 W/kg can lead to a wide range of temperature rises larger than the ones directly enforced here. Although it implies greater complexity than in SAR management, a lot can already be achieved by concatenating a few sequences whose pulses have been designed independently, the resulting overall maximum temperature rise being upper-bounded by the sum of the individual temperature constraints.

Conclusion: A tractable RF pulse design algorithm under strict temperature *rise* constraints and via TVOPs was reported, which is applicable to any linear temperature model. Within the context of Pennes' bio-heat equation, the algorithm here benefitted from the lack of direct correspondence between the temperature and the peak 10-g SAR to return more powerful and safer RF pulses.



References: 1. N. Boulant et al. MRM 2014;72:679-688. 2. J. Lee et al. MRM 2012;67:1566-1578. 3. S. K. Das et al. Med Phys 1999;26:319-328. 4. A. Hoyos-Idrobo et al. IEEE TMI 2014;33:739-748. 5. S. Schmitter et al. MRM 2012;68:188-197.6. M. A. Cloos et al. MRM 2012;67:72-80.

Fig.1: Flip angle distributions (a) and corresponding temperature rises (b) for the 6 min TOF sequence. From top to bottom, the results are for a pulse design under strict SAR, 1 °C, 1.5 °C and 2 °C temperature rise constraints respectively.

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