Published in final edited form as:

Magn Reson Med. 2016 January ; 75(1): 249–256. doi:10.1002/mrm.25637.

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

Nicolas Boulant¹, Xiaoping Wu², Gregor Adriany², Sebastian Schmitter², Kamil Uurbil², and Pierre-François Van de Moortele²

¹CEA, DSV, I2BM, NeuroSpin, Unirs, Gif sur Yvette 91191, France

²Center for Magnetic Resonance Research, University of Minnesota, Minneapolis, MN 55455, USA

Abstract

Purpose—A method utilizing parallel transmission to mitigate B1+ inhomogeneity while explicitly constraining the temperature rise is reported and compared to a more traditional SAR-constrained pulse design.

Methods—Finite difference time domain simulations are performed on a numerical human head model and for a 16 channels coil at 10.5 Tesla. Based on a set of pre-simulations, a virtual observation point compression model for the temperature rise is derived. This compact representation is then used in a nonlinear programming algorithm for pulse design under explicit temperature rise constraints.

Results—In the example of a time-of-flight sequence, radiofrequency pulse performance in some cases is increased by a factor of two compared to SAR-constrained pulses, while temperature rise is directly and efficiently controlled. Pulse performance can be gained by relaxing the SAR constraints, but at the expense of a loss of direct control on temperature.

Conclusion—Given the importance of accurate safety control at ultra-high field and the lack of direct correspondence between SAR and temperature, this work motivates the need for thorough thermal studies in normal in-vivo conditions. The tools presented here will possibly contribute to safer and more efficient MR exams.

Keywords

Parallel transmission; ultra-high field; temperature; optimization; virtual observation points

Introduction

Although there is a general consensus that temperature is the most relevant radiofrequency (RF) related safety parameter (1,2), tracking specific absorption rate (SAR) in MR exams and in RF pulse design has remained the gold standard, which can probably be explained by the complexity of bio-heat equation models, the multi-factorial dependence of temperature

and the lack of fast temperature mapping methods. While RF coil technology, static magnetic field strength and temperature guidelines (2) have evolved throughout the years, SAR safety limits on the other hand have pretty much remained identical, at least in the normal safety mode defined by the International Electrotechnical Commission (IEC) (2). Several numerical studies have recently explored the consistency between the SAR and temperature guidelines in MR exams utilizing parallel transmission (pTx). In (3), a series of thermal simulations conducted on a numerical human head model containing 20 anatomical structures verified over a thousand of different RF shim scenarios the compliance of the 10-g SAR peak limit with the absolute temperature safety guidelines for 30 minutes of RF exposure at 7 T. The same work also showed that a peak 10-g SAR value of 10 W/kg could lead to a wide range of possible temperature values, a consequence of the multi-factorial dependence of temperature, sometimes far from the temperature safety limits. Motivated by this observation, the RF pulse design for a Time-Of-Flight (TOF) sequence under strict absolute temperature constraints was investigated (4), whereby strict SAR constraints (5) were adjusted in a feedback-based manner to fulfill the absolute temperature constraints and provide better RF excitation uniformity. Nevertheless, although the IEC guidelines in general involve upper limits for *absolute* temperature, the latter actually appears quite dependent on daily fluctuations caused by uncontrolled events occurring in the patient's life (fever, physical activity, stress, weather etc); furthermore, in vivo absolute temperature measurement with MR is still extremely challenging (6). As a result, controlling temperature rise at this point seems a more realistic and practical approach.

A 10.5 T MRI scanner for human studies has recently been installed at the Center for Magnetic Resonance Research of the University of Minnesota. Accurate safety control at this unprecedented field strength is critical. Using ultra-conservative power limits however would prevent from exploiting the full potential of this scanner. Within this framework, we report an RF pulse design algorithm which explicitly controls the local temperature rise via a compression model similar to the Virtual Observation Points (VOPs) compression of SAR matrices (7, 8), used to design SAR-constrained pulses (5, 9). Thermal pre-simulations are first carried out for a given sequence time, coil and head model to obtain complex temperature $\mathbf{T}$ matrices (the equivalent of the SAR $\mathbf{Q}$ matrices (10)), after which the compression scheme follows. The thermal model employed here is Pennes' bio-heat equation (11). As it will be shown, focusing on the temperature rise instead of the absolute temperature allows to conveniently drop uncertain parameters from the equation, making this variable more robust and less prone to errors. The algorithm used for RF pulse design is the active-set (A-S) method previously shown to be fast, robust and powerful for this particular kind of nonlinear programming problem (5). The theory is developed and illustrated in the next sections with numerical simulations performed for a TOF sequence with various sequence durations at 10.5 T.

Methods

Thermal model

A general linear absolute temperature model may be written as:

$$\rho c_p \frac{\partial T}{\partial t} = f(T) + g + \rho \text{SAR}, \quad [1]$$

where ρ is the tissue density (kg/m^3), c_p the specific heat capacity (J/kg/K), T the local temperature (K) and f is a linear function of temperature. The term g is independent of the RF source and of the temperature. It leads to a nonzero equilibrium temperature in the absence of RF: $f(T_{\text{eq}}) + g = 0$, which simply expresses the balance between heat production (e.g. with metabolism) and heat losses (conduction, perfusion) in this condition. All terms may be spatially dependent. In the case of Pennes' bio-heat model, the different terms are:

$$f(T(r)) = \vec{\nabla} \cdot (k(r) \vec{\nabla} T(r)) - B(r)T(r) \text{ and } g(r) = B(r)T_b(r) + C(r), \quad [2]$$

where k is the thermal conductivity (W/K/m), B the perfusion constant (W/K/m^3), T_b the time-independent (but possibly spatially dependent) blood temperature (K) and C is the metabolic rate (W/m^3). Exploiting the linearity of f and setting the absolute temperature $T(r)$ equal to the equilibrium temperature $T_{\text{eq}}(r)$ plus the temperature rise $\Delta T(r)$ yield for the latter:

$$\rho c_p \frac{\partial \Delta T}{\partial t} = f(\Delta T) + \rho \text{SAR}, \quad [3]$$

i.e. g , which contains T_b and C in the case of Pennes' model, drops out of the equation. In this description, the temperature rise thus does not depend on the equilibrium temperature and on some possibly uncertain function g .

Temperature matrices and compression scheme

The SAR can be calculated by using $\mathbf{Q}(\mathbf{r})$ Hermitian local matrices defined for every voxel as $Q(r) = \frac{\sigma}{2\rho} (E_x^\dagger E_x + E_y^\dagger E_y + E_z^\dagger E_z)$ (10), where $E_{x,y,z}$ is the normalized complex row vector containing the electric field values coming from each channel and for the corresponding axis, at location r . Given N_T -point time waveforms dispatched on N_c channels, I_c being the N_T by N_c array containing all these waveforms, for 100 % duty cycle the SAR at voxel r is given by (10):

$$\text{SAR}(r) = \frac{1}{N_T} \sum_{i,j}^{N_c} Q_{i,j}(r) (I_c^\dagger I_c)_{i,j}, \quad [4]$$

where i and j refer respectively to the row and column indices of the corresponding matrices. Equation 3 being linear with respect to the RF heat source, one can numerically solve it for each $Q_{i,j}(r)$ map to obtain for a given duration a corresponding $T_{i,j}(r)$ complex distribution which is a solution of:

$$\rho c_p \frac{\partial \Delta T_{i,j}(r)}{\partial t} = f(\Delta T_{i,j}(r)) + \rho Q_{i,j}(r). \quad [5]$$

Because $Q_{ij}(r)$ and $Q_{ji}(r)$ are complex conjugates, by construction so are $T_{ij}(r)$ and $T_{ji}(r)$. Hence after $N_c(N_c+1)/2$ (pre-) computations, by exploiting the linearity of the model the temperature rise $T(r)$ at any point likewise can be calculated using $\mathbf{T}(r)$ complex matrices:

$$\mathbf{T}(r) = \begin{bmatrix} \Delta T_{1,1}(r) & \cdots & \Delta T_{1,N_c}(r) \\ \vdots & \ddots & \vdots \\ \Delta T_{N_c,1}(r) & \cdots & \Delta T_{N_c,N_c}(r) \end{bmatrix}, \quad [6]$$

so that for any waveform array $\mathbf{I}_c$, one obtains:

$$\Delta T(r) = \frac{1}{N_T} \sum_{i,j}^{N_c} \Delta T_{i,j}(r) (\mathbf{I}_c^\dagger \mathbf{I}_c)_{i,j}. \quad [7]$$

For a static RF shim with $\mathbf{x}$ the vector containing the N_c complex weights, the previous result simply becomes $T(r) = \mathbf{x}^\dagger \mathbf{T}(r) \mathbf{x}$. This pre-simulation idea was used in (12) to speed up the computation of the temperature rise for fast hyperthermia optimization. In this work precomputations were done by using a home-made finite difference time domain (FDTD) method with 2 s integration time step and 4 mm isotropic spatial resolution to solve Pennes' equation (3). Drawing the parallel with the SAR and the $\mathbf{Q}$ matrices, a similar Temperature VOP (TVOP) compression scheme now can be derived (7, 8). By defining T_G the average temperature rise (with a corresponding temperature matrix) over the whole volume, one can define the TVOPs as the set of $\mathbf{T}$ matrices, which guarantees that $\exists k \in \text{TVOPs}$ such that $T_k \max(T(r)) \leq T_k + \lambda T_G$, where λ is the tolerance factor which controls the level of compression and T_k denotes the temperature rise calculated for the k^{th} TVOP. Following the work in (8), the $\mathbf{T}$ matrices are first sorted according to their maximum eigenvalues in decreasing order. The set of TVOPs then is initialized as the first $\mathbf{T}$ matrix in the list. The algorithm afterwards proceeds and searches for a set of N positive coefficients c_n , N being the current number of TVOPs, whose sum is unity $\sum_n^N c_n = 1$ and such that $\sum_{n=1}^N c_n \mathbf{TVOP}_n + \lambda \mathbf{T}_G - \mathbf{T}$ is nonnegative, where $\mathbf{T}$ is a candidate **TVOP** and $\mathbf{T}_G$ is the global temperature matrix (returning the average temperature rise scalar quantity T_G). If such a set of coefficients is found, the candidate $\mathbf{T}$ matrix is not retained as a TVOP. Otherwise, it becomes an additional TVOP. Other algorithmic details to compute VOPs can be found in (7, 8). Because the $\mathbf{T}$ matrices depend on the duration of the RF exposure (Eq. 5), so do the TVOPs. In this work, sequence durations of 6, 10 and 30 min were taken. By construction of the TVOPs, it is thereby ensured that the maximum temperature rise over the full model is always upper-bounded by one of the TVOPs plus the defined tolerance, and lower bounded by the maximum over the TVOPs. Once the TVOPs were computed by following the derivation above and the algorithm in (8), they were validated by calculating over 20000 random square RF waveforms (uniform distribution in amplitude and phase) of constant amplitude and phase the maximum temperature rise over these TVOPs, the same temperature plus the tolerance, and the temperature rise using the full model. Each random waveform was scaled in order to yield a total power equal to 10 W. In a separate calculation, the same random waveforms were scaled to yield a peak 10-g SAR equal to 10 W/kg to

calculate the range of possible temperatures achievable when reaching this SAR limit, depending on sequence duration. Throughout this study, the SAR source (Eq. 4) taken to compute the $\mathbf{T}$ matrices (Eq. 5) was always the equivalent continuous-wave SAR which, as shown in (13), leads to a very slight overestimation of the temperature compared to an equivalent time-average SAR obtained in a pulsed mode.

Electromagnetic simulations

FDTD-based electromagnetic simulation software SEMCAD X v14.8 (Speag, Zurich, Switzerland) was used to perform the simulation of the B_1 and electric fields. The coil model reproduced an elliptical 16-channel RF microstrip transceiver coil that was utilized in experiments at 7 T (see Fig. 1) (14) with adjusted dimensions (length of the dipoles shortened to 11 cm and 7 cm for the long and small elements respectively) for application at 10.5 T. The coil was iteratively tuned and matched at 450 MHz ($S_{ii} < -8$ dB). The 2 mm isotropic resolution Duke head model from the virtual family (shoulders included) was used for the simulations. Once computed, field maps were eventually downsampled to a $4 \times 4 \times 4$ mm³ grid to make the SAR and thermal calculations more tractable. After computing the $\mathbf{Q}$ matrices for each voxel, the $\mathbf{Q}_{10g}$ matrices were constructed to calculate 10-g SAR values by using a region-growing algorithm. The global SAR $\mathbf{Q}_G$ matrix was obtained by averaging the energy density over the relevant mass (2). With all these $\mathbf{Q}$ matrices available, the $\mathbf{T}$ matrices and TVOPs could be computed for each sequence duration, as explained in the previous sub-section.

It is important to note however that while SAR averaging guidelines (10-g or global) conveniently dilute the spurious electric field spikes due to stair-casing errors in FDTD simulations, temperature calculations arising from voxel-wise SAR distributions are more sensitive to numerical artifacts and can lead to unrealistic temperature rises, even when taking into account heat diffusion effects (such spikes may lead to special SAR averaging rules at the skin interface (2), i.e. where large discontinuities in conductivity occur). Note that, yet, computing the electric field peak value is important for low frequency RF exposures (1 Hz – 100 kHz), which can e.g. induce peripheral nerve stimulations (15). Recommendations issued from the International Commission of Non-Ionizing Radiation Protection (ICNIRP) for that purpose exist (15–17) but do not seem to apply when the exposure is non uniform (17). Due to the speckle noise nature of these spurious spikes (17), in this work a $3 \times 3 \times 3$ median filter was thus applied to the E-field distributions for each channel, due to the efficiency of this filter to remove this particular kind of noise (18). In any case, the filtered E-field distributions were used both for SAR and temperature calculations.

RF pulse design

The previous sections described the formalism used throughout to speed up the calculation of the temperature rise and enforce corresponding thresholds, via the $\mathbf{T}$ matrices and the TVOPs. To solve the Magnitude Least Squares (MLS) (19) pulse design problem under strict temperature rise and peak power constraints, the A-S algorithm was used given its demonstrated success to solve this problem under strict SAR constraints (4, 5). For this TOF example, the problem is defined as the following:

$$\min_{\mathbf{x}} \left(\mathbf{x} = \begin{bmatrix} \mathbf{x}_B \\ \mathbf{x}_T \end{bmatrix} \right) = \left\| \begin{bmatrix} \mathbf{A}_B & 0 \\ 0 & \mathbf{A}_T \end{bmatrix} \begin{bmatrix} \mathbf{x}_B \\ \mathbf{x}_T \end{bmatrix} - \begin{bmatrix} \boldsymbol{\theta}_B \\ \boldsymbol{\theta}_T \end{bmatrix} \right\|_2^2 = \|\mathbf{A}\mathbf{x} - \boldsymbol{\theta}\|_2^2, \quad [6]$$

$$\text{s.t. } c_i(\mathbf{x}) \leq T_{\max}, i=1 \dots N_{\text{TVOPs}},$$

$$c_{p,k}(\mathbf{x}) = |\mathbf{x}_k|^2 \leq 2 \text{ kW}, k=1 \dots N_c N_{kT}.$$

The matrices $\mathbf{A}_B$ and $\mathbf{A}_T$ have the units of flip angle per square root of W and encode the spins' dynamics in the Small Tip Angle Approximation (STA) (20, 21) for the bottom and top slabs of the brain where 20° (θ_B) and 60° (θ_T) flip angles are targeted, respectively (see Fig. 2). The method used is the k_T -spokes technique (4, 22) so that $\mathbf{x}_B$ and $\mathbf{x}_T$ are 2 and 3 k_T -spokes pulses respectively, and where each sub-pulse is a 1 ms-sinc pulse apodized with a Hanning window and with time-bandwidth product equal to 4. The constraints c_i and $c_{p,k}$ denote the temperature rise for each TVOP and the peak power constraints respectively. The duty-cycle was taken as 20 % (23). The A-S algorithm was implemented here via the optimization toolbox of Matlab (The Mathworks, Natick, MA, USA). It is an iterative (Quasi-Newton) procedure where at each step the problem is approximated by a quadratic program (QP) with the constraints linearized (24). Computational details and analytical formula for calculating the objective function, the constraints as well as their respective gradients can be found in (5). For both SAR and temperature-constrained pulse designs, the number of iterations, i.e. the number of times the QP was solved, was set to 300. The CPU times provided in this paper are for a workstation equipped with a 3.2 GHz Intel Xeon processor (Intel, Santa Clara, CA) and 12 GB of RAM.

The pulse performance under these constraints here was studied for 6, 10 and 30 minutes TOF sequence durations and with $T_{\max} = 1, 1.5$ and 2°C . The resulting peak 10-g and global SAR values were calculated but no limits regarding these values were enforced in the algorithm. For comparison and to emphasize the lack of direct correspondence between the SAR and temperature rise, the same A-S was implemented in another instance with hard 10-g SAR and global SAR constraints (5), i.e. with the SAR limits issued by the IEC and with the ones returned by the temperature-constrained pulse designs; this time, the resulting temperature rise was computed.

Results

An illustration of the VOPs (both temperature and SAR) is provided in Fig. 3 for two sagittal slices and for an equal number of VOPs (389) obtained with $\lambda = 10$ and $T_{\text{acq}} = 30$ min. In agreement with previous studies (1, 3), the dependence of temperature is multifactorial and does not simply depend on the SAR hotspots. The locations of the TVOPs (right of the figure) shown as white squares are not correlated with the ones of the SAR VOPs (left of the figure). While the SAR VOPs can indeed be located deep inside the brain, the TVOPs are mostly in the low-perfused regions (e.g. skin, muscle, CSF). The compressibility of the model improved with the duration of the sequence, e.g. with $\lambda = 10$ in all cases, the resulting number of TVOPs was 551, 483 and 389 for the 6, 10 and 30 min sequences respectively.

Figure 4 shows with 20000 random waveforms the validation of the TVOPs (for a 6 min sequence) with the maximum temperature rise calculated over the TVOPs, the same temperature plus the defined tolerance and the one calculated over the full model. The latter is always upper-bounded by the TVOPs plus the tolerance and lower-bounded by the TVOPs. Moreover, Figure 5 provides histograms of the maximum temperature rises for 6, 10 and 30 min RF exposures, computed with the same 20000 random RF scenarios. This time, however, results were scaled so that the peak 10-g SAR was always equal to 10 W/kg. The global SAR safety limit of 3.2 W/kg on the other hand was never reached. Despite the peak 10-g SAR being always the same, one can see that the maximum temperature rise can reach a range of different values, showing that there is no one-to-one mapping between the peak 10-g SAR and the maximum temperature rise. Also the longer the sequence, the wider the temperature distribution becomes, with a double hump furthermore appearing for the 30 min sequence.

Table 1 summarizes the results of the pulse design using the A-S algorithm under various constraints, for the 6, 10 and 30 min TOF sequences. The A-S algorithm converged to a local minimum after 300 iterations in about 30 s for the SAR and temperature-constrained pulse designs. The peak power constraint ($=2$ kW) was always saturated. For sequence durations up to 30 min, in our example the pulse design under strict temperature rise constraints clearly outperforms with a lower Normalized Root Mean Square Error (NRMSE) the one under strict SAR constraints already with 1 °C rise constraint, the gain increasing with decreasing sequence duration. For completeness, the resulting SAR values are also provided. If the returned SAR values are taken as new constraints for pulse design, the numbers in the table also show that lower NRMSEs could be achieved but with a loss of direct control on temperature, leading to larger temperature rises than the ones otherwise enforced. Hence SAR limits can potentially be increased to obtain smaller NRMSEs but with no guarantee of fulfilling the desired temperature criterion. Moreover, if the temperature rise returned by the IEC SAR-constrained design is used as a constraint in pulse design, a better NRMSE is obtained.

For the 6 min sequence, the resulting SAR values for the 1.5 °C-constrained pulse design are about twice larger (21 W/kg) than the SAR limits recommended by the IEC (10 W/kg). A SAR-constrained pulse with this 21 W/kg SAR limit returns a similar NRMSE (8.3 vs. 8.5 %) compared to the 1.5 °C temperature-constrained pulse, but this time leading to a 1.93 °C maximum temperature rise. Despite the loss of control on temperature, in this particular case the results thus show that similar pulse performance could be reached still by fulfilling the IEC SAR safety criteria, but then at the expense of roughly doubling the repetition, hence acquisition, time (the peak SAR value of 21 W/kg thus becoming 10.5 W/kg).

Finally, some simulated flip angle maps are provided for the 6 min sequence in Fig. 6.a. While the target flip angles cannot be achieved, mainly at the coil extremities along the head-foot direction (i.e. in the cerebellum and in the top slab) in the (IEC) SAR-constrained pulse design case, the correct flip angles are obtained as the temperature rise is progressively increased in a controlled manner. The corresponding temperature rises are shown in Fig 6.b where the hot spots mainly occur in the skin and CSF regions.

Discussion

We have reported in this work an efficient algorithm for constraining directly the temperature rise in RF pulse design using pTx at ultra-high field. Although the IEC guidelines generally involve absolute temperature constraints (2), for which some approach has been proposed (4), constraining instead the temperature rise appears at this point more practical. The tools presented here can allow for a direct control of a more relevant safety metric in RF pulse design than the ubiquitously used SAR. While all the considered sequence durations with peak 10-g SAR equal to 10 W/kg could lead to temperature rises higher than 1 °C (Fig. 5), the results provided in Table 1 show that the proposed pulse design can be more powerful and safer, by achieving lower NRMSEs with more controlled temperature rises. Lower NRMSEs for SAR-constrained pulses could be obtained by increasing the repetition time, thereby relaxing SAR constraints, but then at the expense of a larger acquisition time. The same table also shows that SAR constraints can be relaxed to achieve better RF pulse performance, but then with a loss of direct control over the temperature, which increases with sequence duration.

Compared to SAR-constrained techniques, the TVOP approach obviously demands more computing efforts as a different set of TVOPs exists for each sequence duration. However, as long as generic models are used, they can be pre-computed only once. In addition to the VOPs construction algorithm (7, 8), one first has to determine the **T** matrices via a series of thermal simulations (see Eq. 5). Here with a 2 s time step and 4 mm isotropic resolution, the computation of the **T** matrices was performed in 45 min for the 6 minutes sequence and for this 16-channel coil. This step however could be drastically speeded up with the design of appropriate spatial filters (25).

The location of the TVOPs (see Fig. 3) indicates that the maximum temperature rises likely occur in less sensitive regions than the brain (e.g. skin), where the equilibrium temperature (i.e. the steady state obtained without RF source) is less than 37 °C (3), thereby possibly allowing a 1.5–2 °C temperature rise constraint while remaining conservative with respect to the absolute temperature guidelines. With such constraint, the pulse design in our study under strict temperature rise constraints always outperformed in terms of NRMSE the SAR-constrained one at 10.5 T. This is possibly a consequence of the shortening of the wavelength at ultra-high field and the ability of pTx to distribute the energy differently in boxes containing 10-g of contiguous tissue. While the peak 10-g SAR metric indeed summarizes the local SAR values inside the 10-g box with a single (average) number, temperature on the other hand is more sensitive to their distribution. How the same approach would perform at a longer wavelength at the more common field strength of 7 T remains a topic of further investigation. Future work also involves the validation of this technique in-vitro by using tools extracted from the electric properties tomography literature to estimate channel-dependent E-fields (26, 27), and magnetic resonance thermometry (6). Lastly, the MLS optimization problem being non-convex, one can never be sure that a given SAR-constrained design corresponds to the global minimum (i.e. the most flip angle homogenizing solution). The observations made in this work thus partly rely on the robustness of the A-S algorithm to tackle the MLS problem under strict nonlinear

constraints, which was demonstrated elsewhere (5) at 7 T. Other algorithms, which explicitly take the constraints into account, could also be attempted (9, 28, 29).

The model used in this work for the temperature calculations was Pennes' bio-heat model, but the same method can be applied to any model, as long as it is linear. Taking into account a possible dependence of the thermal parameters on temperature (30) would break the linearity. However, disregarding this dependence puts the thermal calculations on the safe side (30). Finally, while SAR averaging (10-g and global) is more robust with respect to stair-casing errors encountered in FDTD simulations, temperature results on the other hand are clearly more sensitive (17). Spurious electric field spikes can occur at interfaces between tissues with highly different conductivities (17), which here were simply filtered out by using a small median filter. Yet, discontinuities in E fields across interfaces are permitted by Maxwell's equations, which makes it difficult to distinguish them from the numerical artefacts. Whether applying a median filter is the optimal way to suppress them is beyond the scope of this paper. As a test, the size of the median filter was increased slightly ($5 \times 5 \times 5$) and the same optimizations were performed for the 6 min sequence. While this led to slightly better SAR-constrained (15.2 % vs. 16.2 % with the SAR IEC guidelines) and temperature-constrained (10.4 % vs. 10.8 % for the 1 °C constraint) NRMSEs due to smaller E-field values, it did not affect qualitatively the results. A possible alternative is to smooth the spatial distribution of the conductivity, at the expense, however, of a loss in anatomical details (17).

The proposed pulse design method also implies a natural increase in complexity compared to SAR-constrained methods because the sliding-integration window used for SAR calculations can no longer be applied, which is especially problematic when different sequences using different RF pulses follow each other. For temperature-constrained pulse design, either a pause should be interleaved between sequences to reset the temperature or the whole exam should be taken into account. On a more positive and practical note, because SAR hotspots in pTx spatially depend on the designed pulses and hence the sequences, and because any bio-heat model will always involve heat diffusion, the resulting temperature rise is at most additive in the worst-case scenario, and less than additive in all other cases. As a result, pulses for two sequences for instance can be designed independently for simplicity, each with a different temperature rise constraint, the resulting overall temperature rise being necessarily upper-bounded by the sum of the two. Yet, it possibly offers more latitude in RF pulse design than if SAR constraints are used. Finally, although the IEC guidelines specify temperature limits without time considerations (2), it remains unknown to the authors whether reaching a given temperature rise of ~1 °C in a short amount of time (~1 min), as the described method would enable to do, would be safe.

Conclusion

We have reported an RF pulse design algorithm which explicitly constrains the temperature rise in the tissues via the use of TVOPs. Although the method was applied to a TOF sequence example, it can be potentially useful for any sequence where SAR is the limiting factor. The examples presented in this study show that better RF excitation can be achieved compared to SAR-constrained pulses without sacrificing duty cycle and while controlling

temperature. In addition to the extra level of complexity, this represents however an additional step in modelling which as a consequence requires thorough in vivo thermal studies.

Acknowledgments

The research leading to these results has received funding from the European Research Council under the European Union's Seventh Framework Program (FP7/2013-2018)/ERC Grant Agreement n. 309674 and from the National Institute of Health (NIH PR41 EB015894). The authors thank various colleagues at NeuroSpin and at CMRR for valuable discussions.

References

1. Collins CM, Liu W, Wang J, Gruetter R, Vaughan JT, Ugurbil K, Smith MB. Temperature and SAR calculations for a human head within volume and surface coils at 64 and 300 MHz. *J Magn Reson Imaging*. 2004; 19:650–656. [PubMed: 15112317]
2. International Electrotechnical Commission. International standard, medical electrical equipment - part 2: particular requirements for the safety of Magnetic Resonance equipment for medical diagnosis. 3. Geneva: International Electrotechnical Commission; 2011.
3. Massire A, Cloos MA, Luong M, Amadon A, Vignaud A, Wiggins CJ, Boulant N. Thermal simulations in the human head for high field MRI using parallel transmission. *J Magn Reson Imaging*. 2012; 35:1312–1321. [PubMed: 22241685]
4. Boulant N, Massire A, Amadon A, Vignaud A. RF pulse design in parallel transmission and under strict temperature constraints. *Magn Reson Med*. 2014; 72:679–688. [PubMed: 24155266]
5. Hoyos-Idrobo A, Weiss P, Massire A, Amadon A, Boulant N. On variant strategies to solve the magnitude least squares RF pulse design problem in parallel transmission and under strict SAR and power constraints. *IEEE Trans Med Imag*. 2014; 33:739–748.
6. Rieke V, Pauly Butts K. MR Thermometry. *J Magn Reson Imaging*. 2008; 27:376–390. [PubMed: 18219673]
7. Eichfelder G, Gebhardt M. Local Specific Absorption Rate Control for Parallel Transmission by Virtual Observation Points. *Magn Reson Med*. 2011; 66:1468–1476. [PubMed: 21604294]
8. Lee J, Gebhardt M, Wald LL, Adalsteinson E. Local SAR in Parallel Transmission Pulse Design. *Magn Reson Med*. 2012; 67:1566–1578. [PubMed: 22083594]
9. Guérin B, Gebhardt M, Adalsteinson E, Wald LL. Local specific absorption rate (SAR), global SAR, transmitter power, and excitation accuracy trade-offs in low flip-angle parallel transmit pulse design. *Magn Reson Med*. 2014; 71:1446–1457. [PubMed: 23776100]
10. Graesslin I, Homann H, Biederer S, Börner P, Nehrke K, Vernickel P, Mens G, Harvey P, Katscher U. A Specific Absorption Rate Prediction Concept for Parallel Transmission MR. *Magn Reson Med*. 2012; 68:1664–1674. [PubMed: 22231647]
11. Pennes HH. Analysis of tissue and arterial blood temperatures in the resting human forearm. *J Appl Physiol*. 1948; 1:93–122. [PubMed: 18887578]
12. Das SK, Clegg ST, Samulski TV. Computational techniques for fast hyperthermia temperature optimization. *Med Phys*. 1999; 26:319–328. [PubMed: 10076991]
13. Wang, Z.; Smith, MB.; Collins, CM. Dependence of temperature increase on pulse sequence with equivalent time-average SAR. Proceedings of the 15th International Society of Magnetic Resonance in Medicine; Berlin, Germany. 2007. p. 3247
14. Adriany G, Van de Moortele PF, Ritter J, Moeller S, Auerbach EJ, Akgun C, Snyder CJ, Vaughan T, Ugurbil K. A geometrically adjustable 16-channel transmit/receive transmission line array for improved RF efficiency and parallel imaging performance at 7 tesla. *Magn Reson Med*. 2008; 59:590–597. [PubMed: 18219635]
15. ICNIRP guidelines for limiting exposure to time-varying electric and magnetic fields (1 Hz and 100 kHz). *Health Physics*. 2010; 99:818–836. [PubMed: 21068601]
16. Dawson TW, Potter M, Stuchly MA. Evaluation of modeling accuracy of power frequency field interactions with the human body. *Appl Comput Electromagn Soc J*. 2001; 16:162–72.

17. Laakso I, Hirata A. Reducing the staircasing error in computational dosimetry of low-frequency electromagnetic fields. *Phys Med Biol*. 2012; 57:N25–N34. [PubMed: 22290579]
18. Arce, GR. *Nonlinear Signal Processing: A Statistical Approach*. Wiley; New Jersey, USA: 2005.
19. Setsompop K, Wald LL, Alagappan V, Gagoski BA, Adalsteinsson E. Magnitude least squares optimization for parallel radio frequency excitation design demonstrated at 7 Tesla with eight channels. *Magn Reson Med*. 2008; 59:908–915. [PubMed: 18383281]
20. Pauly J, Nishimura D, Macovski A. A k-space analysis of small tip angle excitation. *J Magn Reson*. 1989; 81:43–56.
21. Boulant N, Hoult DI. High tip angle approximation based on a modified Bloch-Riccati equation. *Magn Reson Med*. 2012; 67:339–343. [PubMed: 22139869]
22. Cloos MA, Boulant N, Luong M, Ferrand G, Giacomini E, Le Bihan D, Amadon A. k_T -points: Short three-dimensional tailored RF pulses for flip-angle homogenization over an extended volume. *Magn Reson Med*. 2012; 67:72–80. [PubMed: 21590724]
23. Schmitter S, Bock M, Johst S, Auerbach EJ, Ugurbil K, Van de Moortele PF. Contrast Enhancement in TOF Cerebral Angiography at 7 T Using Saturation and MT Pulses Under SAR Constraints: Impact of VERSE and Sparse Pulses. *Magn Reson Med*. 2012; 68:188–197. [PubMed: 22139829]
24. Nocedal, J.; Wright, SJ. *Springer Series in Operations Research and Financial Engineering*. 2. New York: 2006. Numerical Optimization.
25. Carluccio G, Erricolo D, Oh S, Collins CM. An approach to rapid calculation of temperature change in tissue using spatial filters to approximate effects of thermal conduction. *IEEE Trans on Biomed Eng*. 2013; 60:1735–1741.
26. Liu J, Zhang X, Van de Moortele PF, Schmitter S, He B. Determining electrical properties based on B1 fields measured in an MR scanner using a multi-channel transmit/receive coil: general approach. *Phys in Med and Bio*. 2013; 58:4395–4408. [PubMed: 23743673]
27. Voigt T, Homann, Katscher U, Doessel O. Patient individual local SAR determination: in vivo measurements and numerical validation. *Magn Reson Med*. 2012; 68:1117–1126. [PubMed: 22213053]
28. Sbrizzi A, Hoogduin H, Lagendijk JJ, Luijten P, Sleijpen GL, Van den Berg CA. Fast design of local N-gram specific absorption rate-optimized radiofrequency pulses for parallel transmit systems. *Magn Reson Med*. 2012; 67:824–834. [PubMed: 22127650]
29. Brunner DO, Pruessmann. Optimal design of multiple channel RF pulses under strict power and SAR constraints. *Magn Reson Med*. 2010; 63:1280–1291. [PubMed: 20432299]
30. Wang Z, Lin JC, Vaughan JT, Collins CM. Consideration of physiological response in numerical models of temperature during MRI of the human head. *J Magn Reson Imaging*. 2008; 28:1303–1308. [PubMed: 18972342]

Figure 1.
Reproduced 16-channel elliptical microstrip transceiver head coil loaded with SEMCAD head model.

Figure 2. Sagittal slice of the human model with top and bottom slabs delimited by dashed lines. The target flip angles are 60° and 20° for the top and bottom slabs respectively.

Figure 3. Locations of the VOPs (left) and of the TVOPs (right) shown as white squares and on two sagittal slices.

Figure 4.

Validation of the temperature virtual observation points for the 6 min sequence. Twenty thousand random RF waveforms were used to compute a SAR distribution which yielded a maximum temperature rise over the full model, a maximum temperature over the TVOPs and a maximum temperature over the TVOPs plus the defined tolerance. The results are scaled for 10 W total RF power.

Figure 5.

Histograms of the maximum temperature rises for different sequence durations, calculated over 20000 random scenarios. The waveforms are scaled to always yield 10 W/kg peak 10-g SAR. The global SAR limit of 3.2 W/kg was never reached.

Figure 6.

Flip angle distributions a) and resulting temperature rises b) for different pulse designs and for the 6 minutes-long sequence. From top to bottom: IEC SAR-constraint pulse design and 1, 1.5, 2 °C temperature-constraint pulse designs. The NRMSEs are also provided in a) for each case. The target flip angles are 60° for the venous saturation slab (top slab) and 20° for the imaging slab (bottom slab).

Table 1

Normalized root mean square error (NRMSE) vs. the different constraints for the 6, 10 and 30 min TOF sequences. The NRMSE here is the average of the NRMSEs corresponding to the top and bottom slabs. The resulting temperature is also calculated when performing a pulse design under strict SAR constraints. Likewise, both the peak 10-g SAR and the global SAR values are calculated when the design is done under strict temperature rise constraints. The peak power constraint of 2 kW was saturated in all the tested cases. The constraints enforced in the algorithm are put in bold for clarity.

6 min				
Constraint	NRMSE (%)	SAR 10g (W/kg)	SAR Global (W/kg)	Temperature (°C)
Temperature	10.8	13.4	5.3	1
Temperature	8.5	21	6.9	1.5
Temperature	8.1	27.3	7.6	2
Temperature	11.4	12.6	4.9	0.91
SAR	9.7	13.4	5.3	1.28
SAR	8.3	21	6.9	1.93
SAR	8.1	27.3	7.6	2.38
SAR (IEC)	16.2	10	3.2	0.91

10 min				
Constraint	NRMSE (%)	SAR 10g (W/kg)	SAR Global (W/kg)	Temperature (°C)
Temperature	12.6	11.5	4.5	1
Temperature	9.0	17.8	6.3	1.5
Temperature	8.3	24.7	7.3	2
Temperature	11.4	12.4	4.8	1.1
SAR	11.2	11.5	4.5	1.38
SAR	8.5	17.8	6.3	2.07
SAR	8.2	24.7	7.3	2.80
SAR (IEC)	16.2	10	3.2	1.10

30 min				
Constraint	NRMSE (%)	SAR 10g (W/kg)	SAR Global (W/kg)	Temperature (°C)
Temperature	15.5	10.7	3.9	1
Temperature	10.6	16.0	5.5	1.5
Temperature	8.7	21.8	6.7	2
Temperature	11.3	14.4	5.1	1.37
SAR	12.9	10.7	3.9	1.60
SAR	9.2	16.0	5.5	2.34
SAR	8.2	21.8	6.7	2.79
SAR (IEC)	16.2	10	3.2	1.37